# Can we distinguish between primordial $k_T$ & parton showers?

Mark D. Baker

September 13, 2012

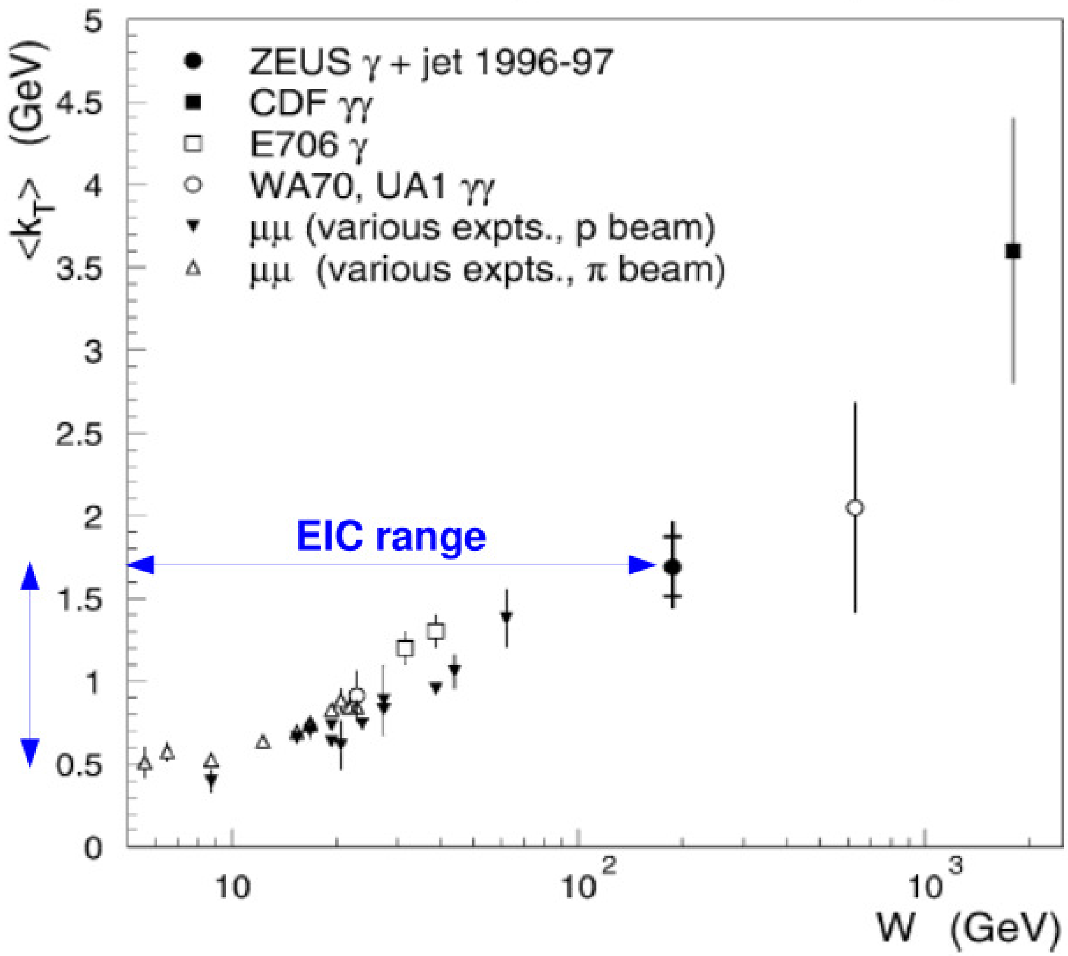
Thanks to: Elke, J.-H., & Raju

# Executive Summary

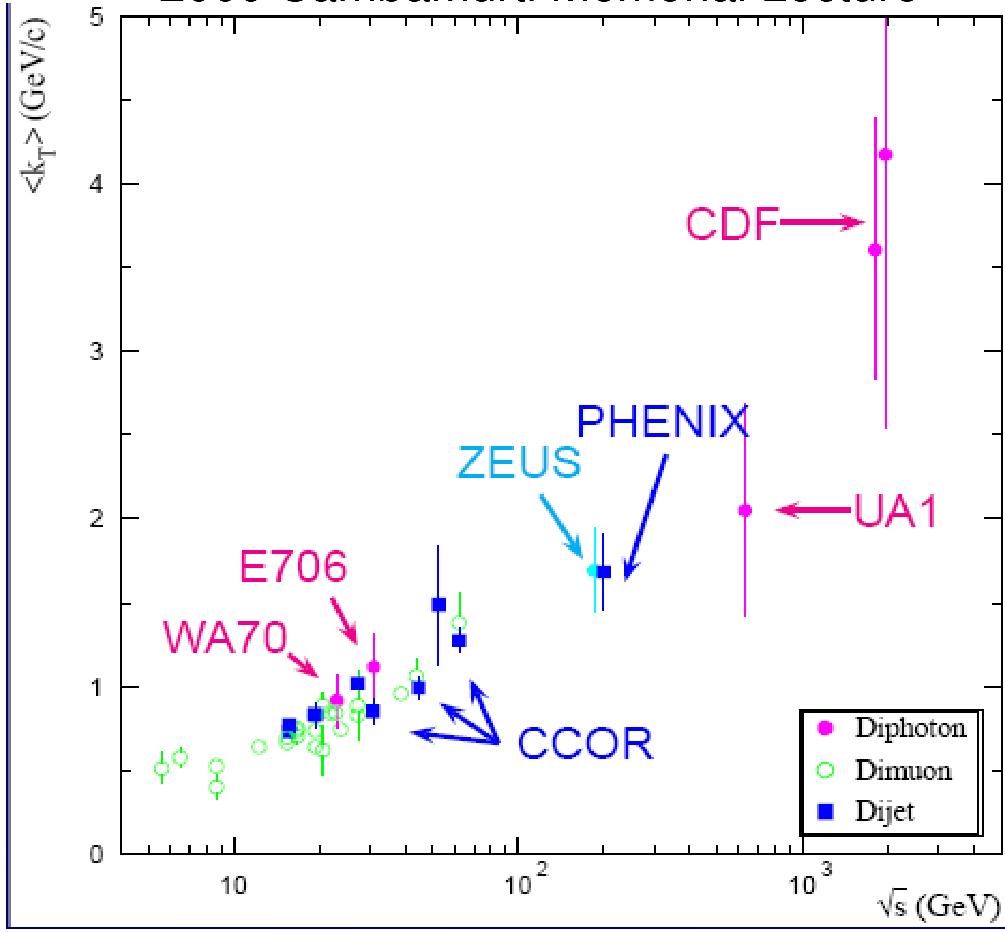
- Yes we can! (at least in ep)
  - Seagull plots: $<p_T^2>$ vs. $x_F$
  - Pt compensation plots
    - A different kind of dihadron correlation
  - Note: we may also want to try the dihadron azimuthal correlation with trigger $z>0.3$ instead of $0.1<z<0.3$.
- Comments on eA and on Drell-Yan

# Running of $k_T$?

ZEUS Collaboration / Physics Letters B 511 (2001) 19–32




M. Begel update for
2009 Sambamurti Memorial Lecture




Note: Gaussian: $\langle k_T \rangle = \mathrm{sqrt}(\pi/4) * k_T^{rms}$

# Running of $k_T$?

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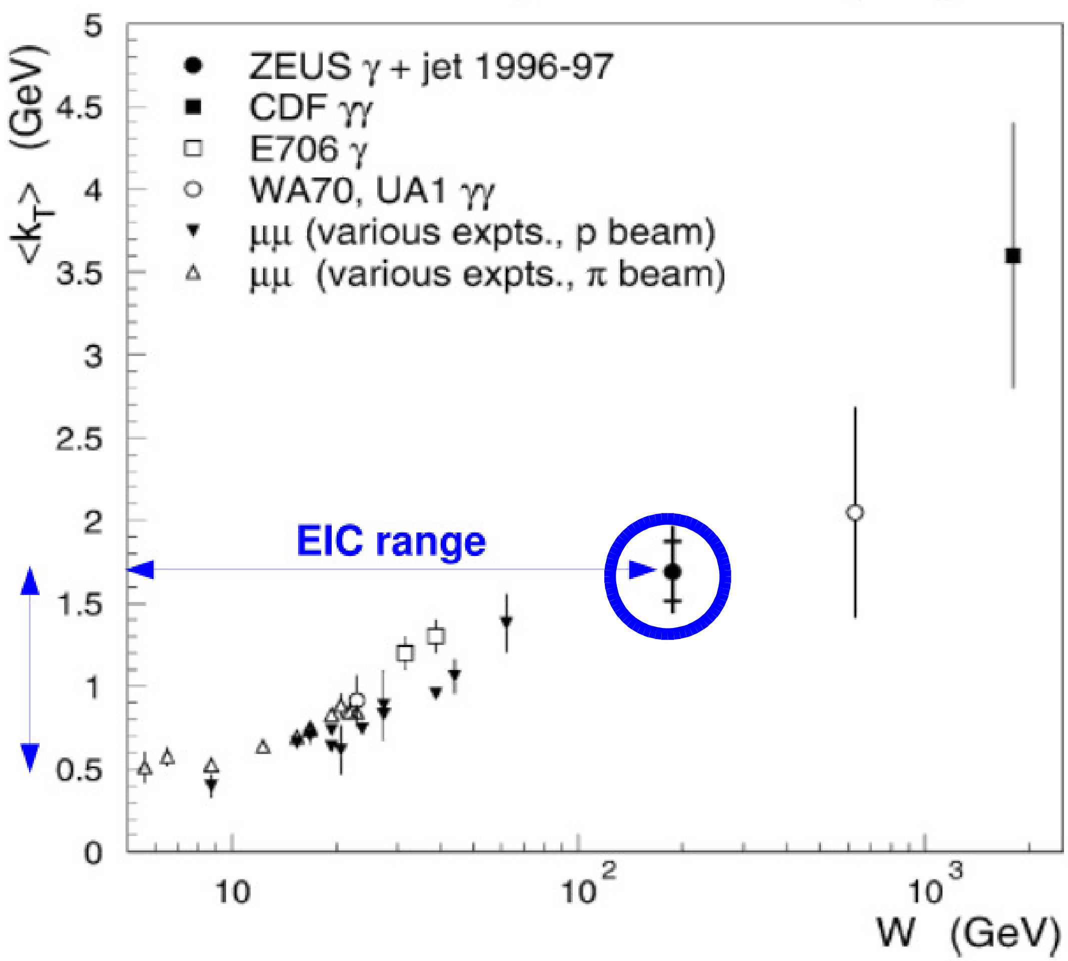


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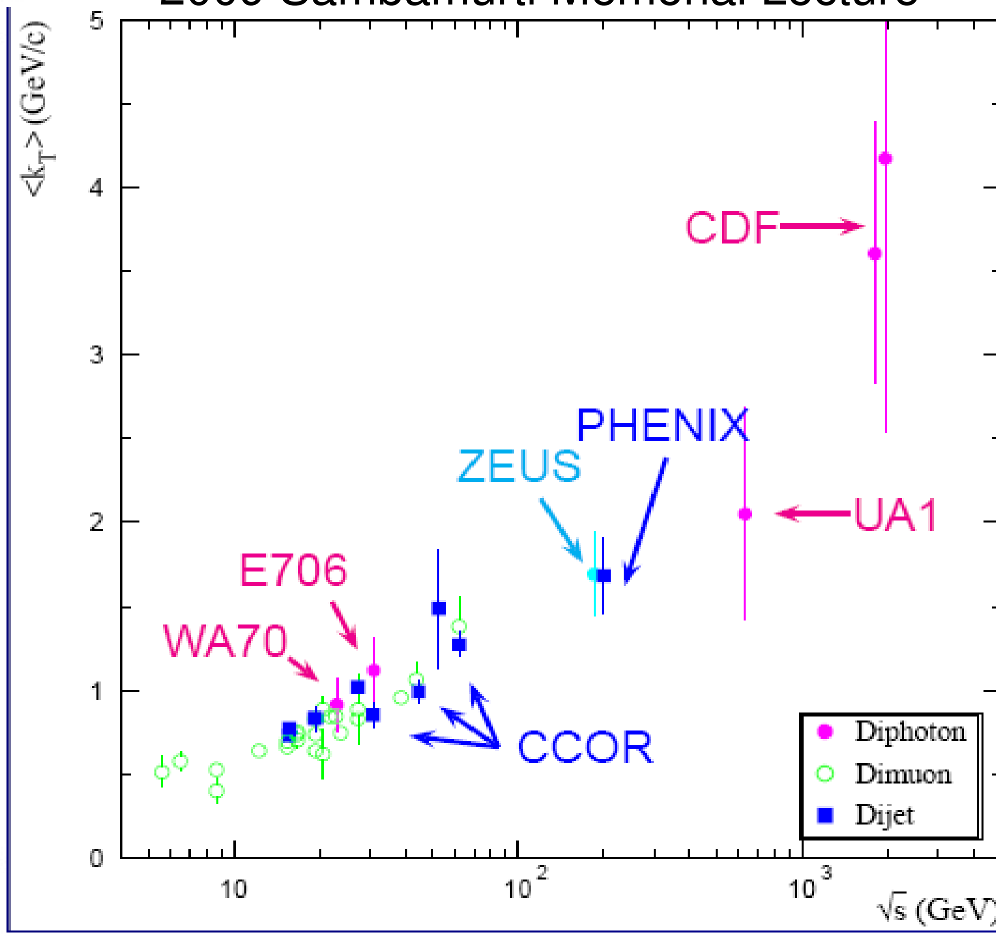
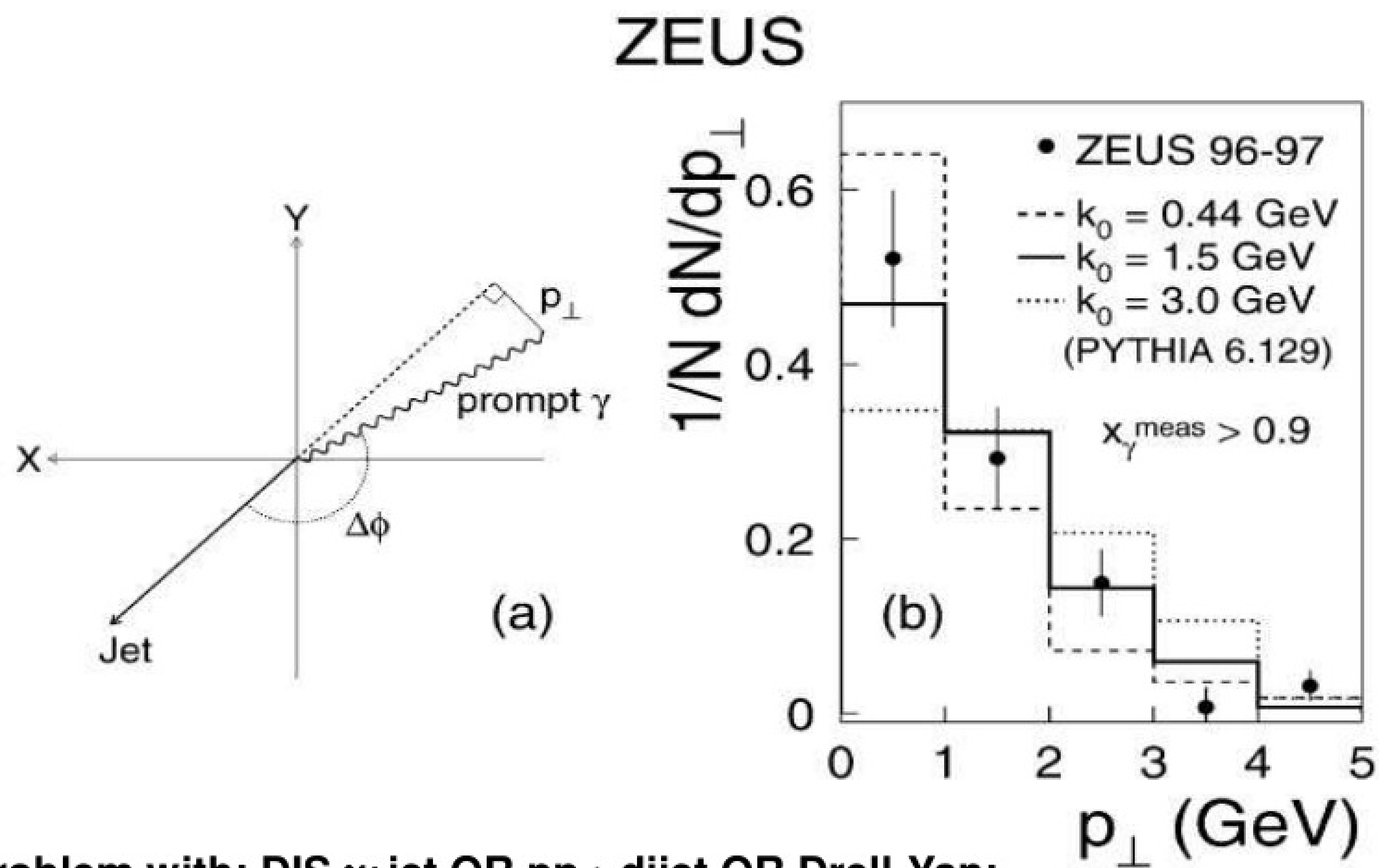



Note: Gaussian: $\langle k_T \rangle = \mathrm{sqrt}(\pi/4) * k_T^{rms}$

# ZEUS-γjet measurement is tricky

*ZEUS Collaboration / Physics Letters B 511 (2001) 19–32*

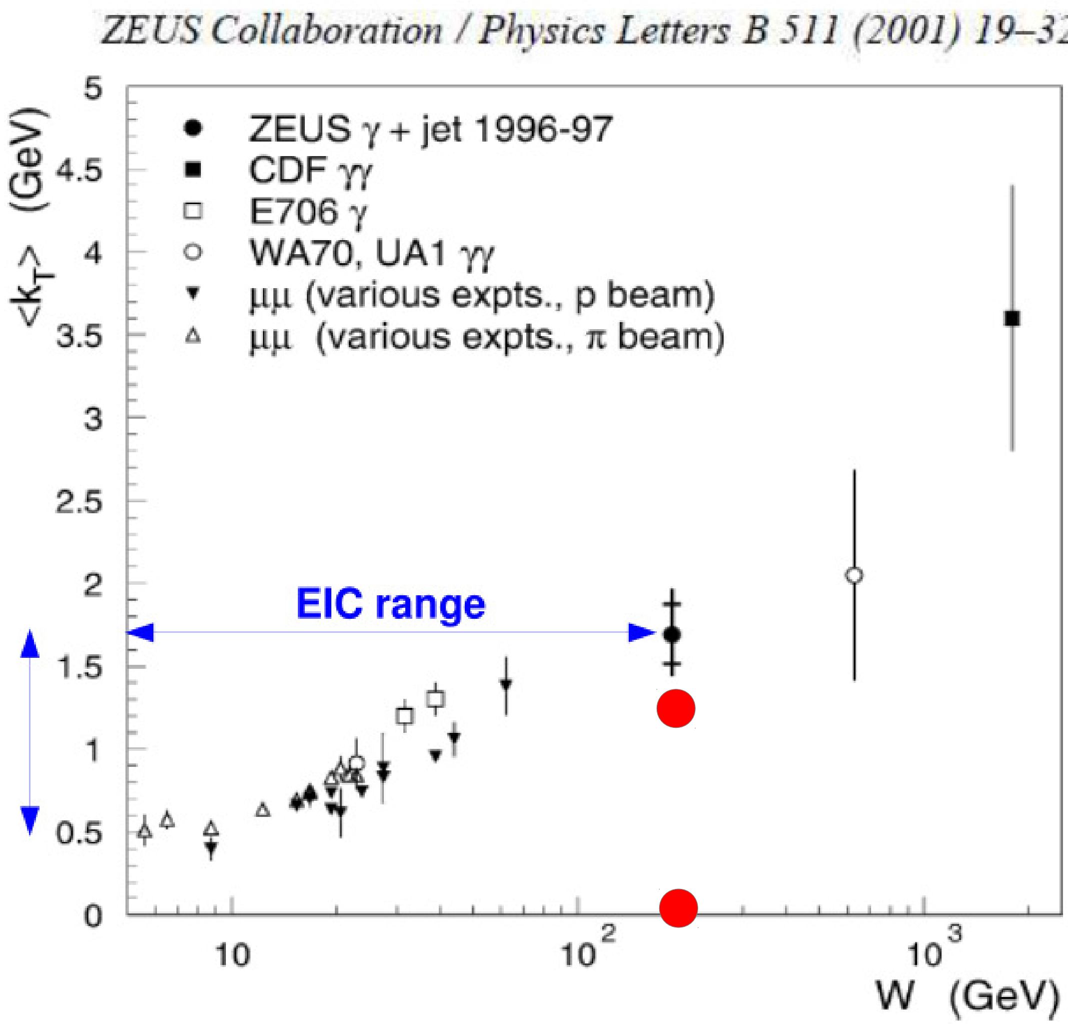



**Common problem with: DIS γ+jet OR pp->dijet OR Drell-Yan:**

**Very <u>subtle</u> differences between intrinsic $k_T$ and gluon radiation**

**We need something that smacks you in the face a bit more...**

# Running of $k_T$?

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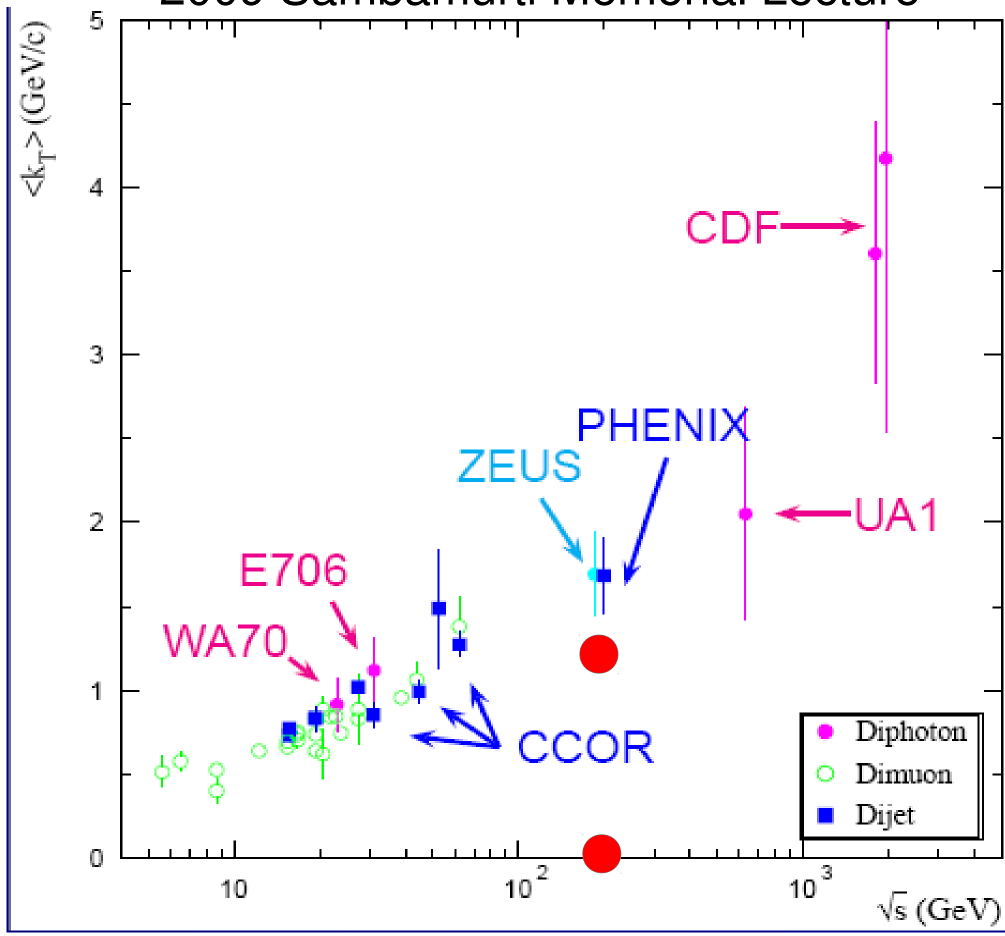



ZEUS $k_T$ total = 1.69 GeV is 1.25 GeV (intrinsic) + parton shower using Pythia 6.1

OR 0 (intrinsic) + ~1.9 GeV parton shower using HERWIG

# Pythia 6.4 Manual describes the problem nicely

### 11.1.4 Primordial $k_\perp$

It is customary to assign a primordial transverse momentum to the shower initiator, to take into account the motion of quarks inside the original hadron, basically as required by the uncertainty principle. A number of the order of $\langle k_\perp \rangle \approx m_\mathrm{p}/3 \approx 300$ MeV could therefore be expected. However, in hadronic collisions much higher numbers than that are often required to describe data, typically of the order of 1 GeV at fixed-target energies[EMC87] and 2 GeV at collider energies [Miu99, Bál01], if a Gaussian parameterization is used. Thus, an interpretation as a purely nonperturbative motion inside a hadron is difficult to maintain.

Instead a likely culprit is the initial-state shower algorithm. This is set up to cover the region of hard emissions, but may miss out on some of the softer activity, which inherently borders on nonperturbative physics. By default, the shower does not evolve down to scales below $Q_0 = 1$ GeV. Any shortfall in shower activity around or below this cutoff then has to be compensated by the primordial $k_\perp$ source, which thereby largely loses its original meaning. One specific reason for such a shortfall is that the current initial-state shower algorithm does not include non-ordered emissions in $Q^2$, as is predicted to occur especially at small $x$ and $Q^2$ within the BFKL/CCFM framework [Lip76, Cia87].

Most measurements, including γ-jet in DIS do not easily distinguish primordial and QCD-shower $k_T$

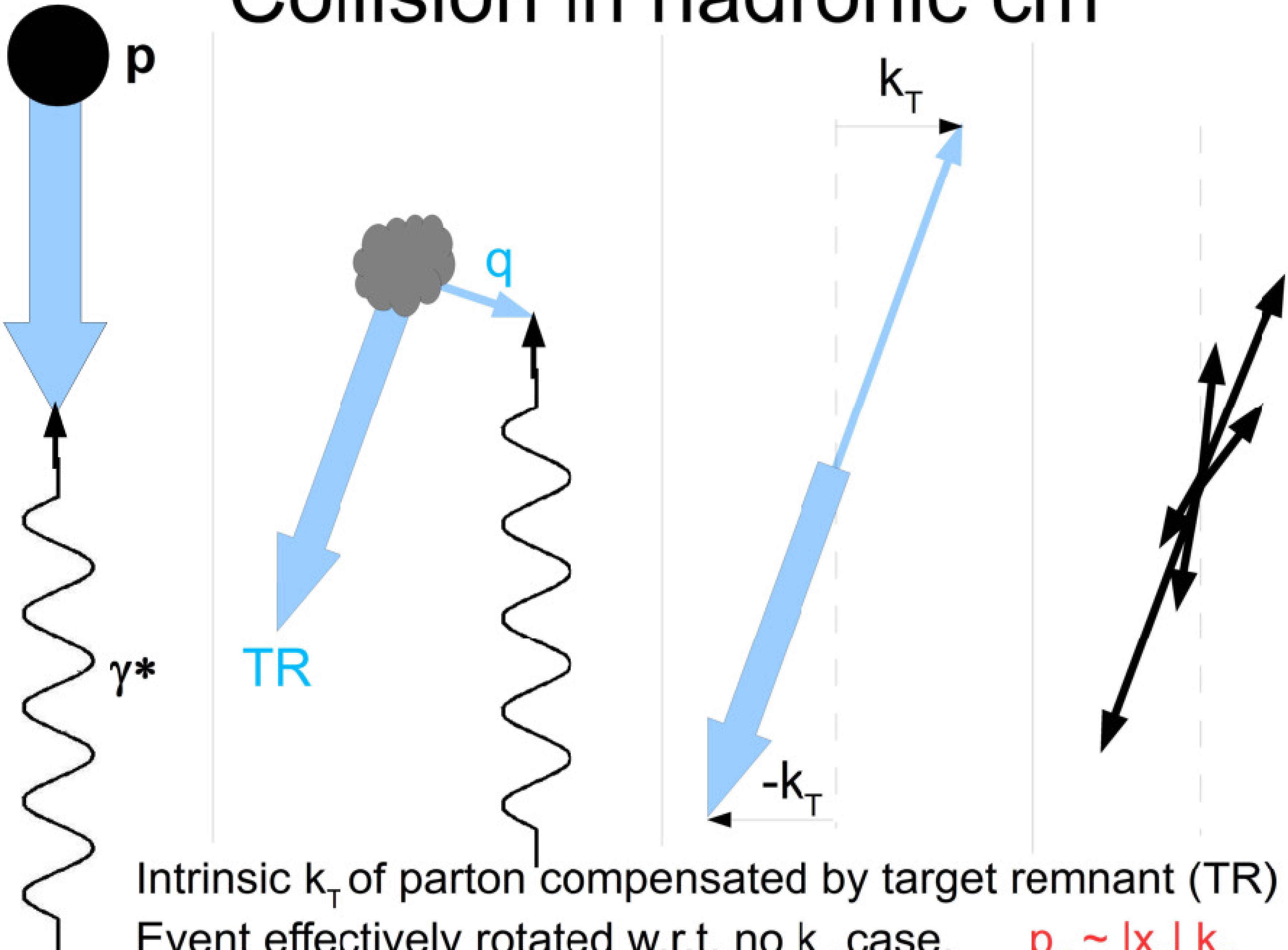
This makes our interpretation of $k_T$, e.g. in terms of $Q_s$, awkward.

Can we find a measurement in ep that distinguishes $k_T$ from PS?

# Kinematics in $\gamma^*p$ cm frame

- +z is virtual photon direction
- Feynman x: $x_F = 2\, p_z/W$, ranges -1 to 1 for ep.
- Cm rapidity: $y^* = \ln[(E+p_z)/(E-p_z)]$

# Collision in hadronic cm

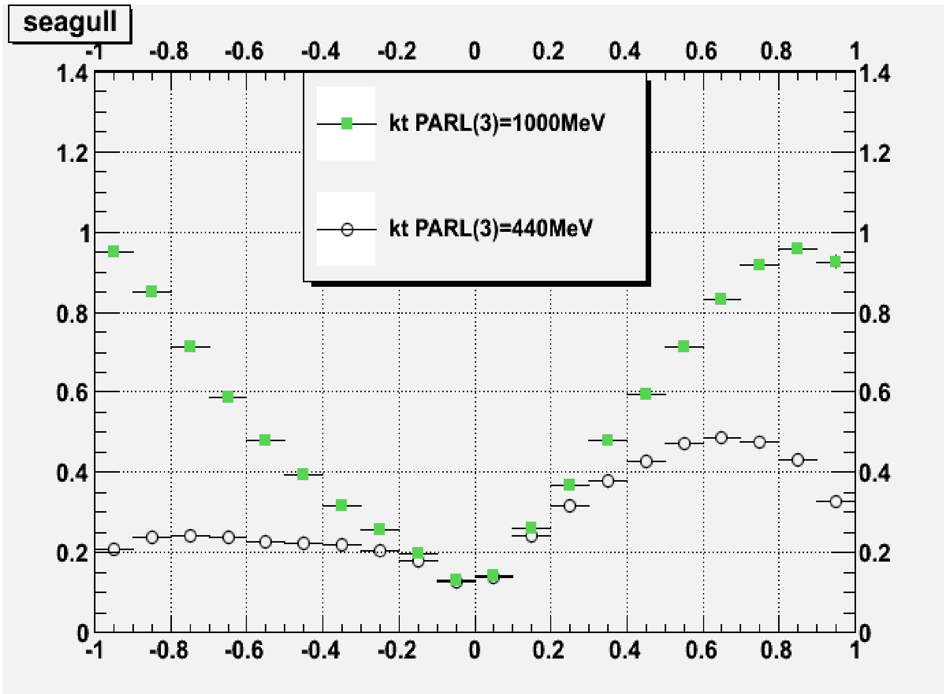



Intrinsic $k_T$ of parton compensated by target remnant (TR)

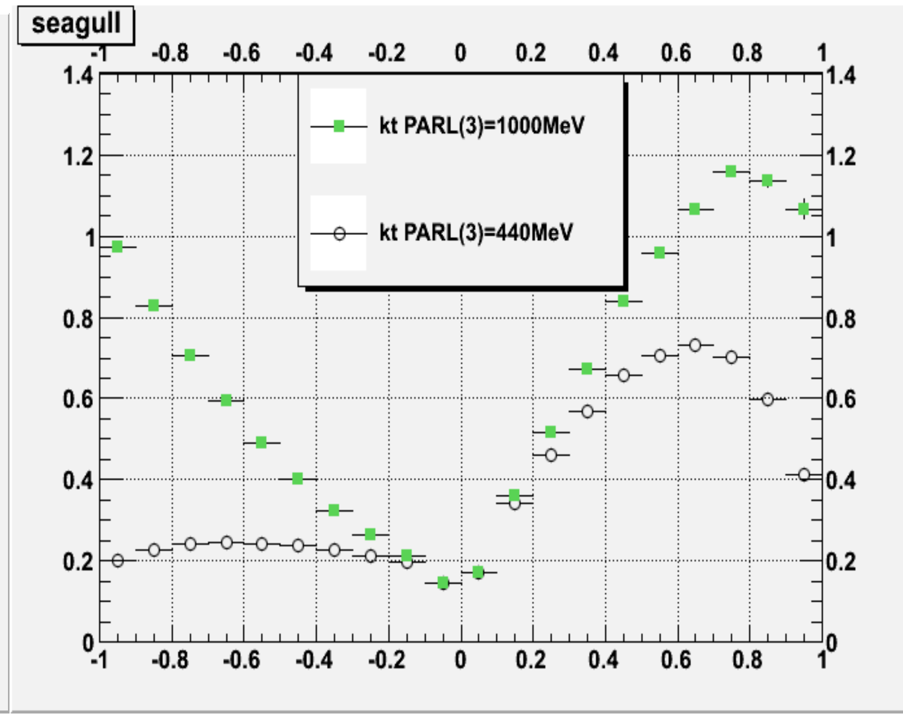
Event effectively rotated w.r.t. no $k_T$ case. $p_T \sim |x_F|\, k_T$

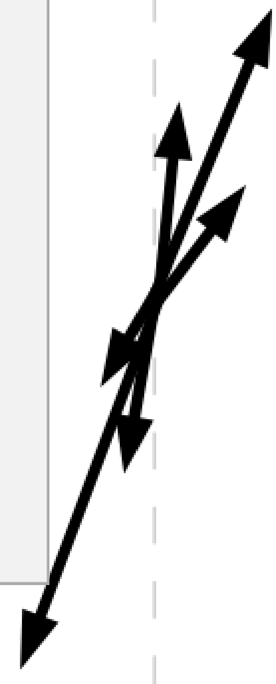
# Primordial $k_T$ shows up at high $|x_F|$

LEPTO 6.5.1 $s=(30\ \text{GeV})^2$
μp 490x0 or ep 5x50 GeV




LEPTO 6.5.1 $s=(140\ \text{GeV})^2$
ep 20x250 GeV



Contribution from primordial $k_T$ to $p_T$ grows with $|x_F|$
& independent of energy (visible in the backward direction)

# Primordial $k_T$ shows up at high $|x_F|$

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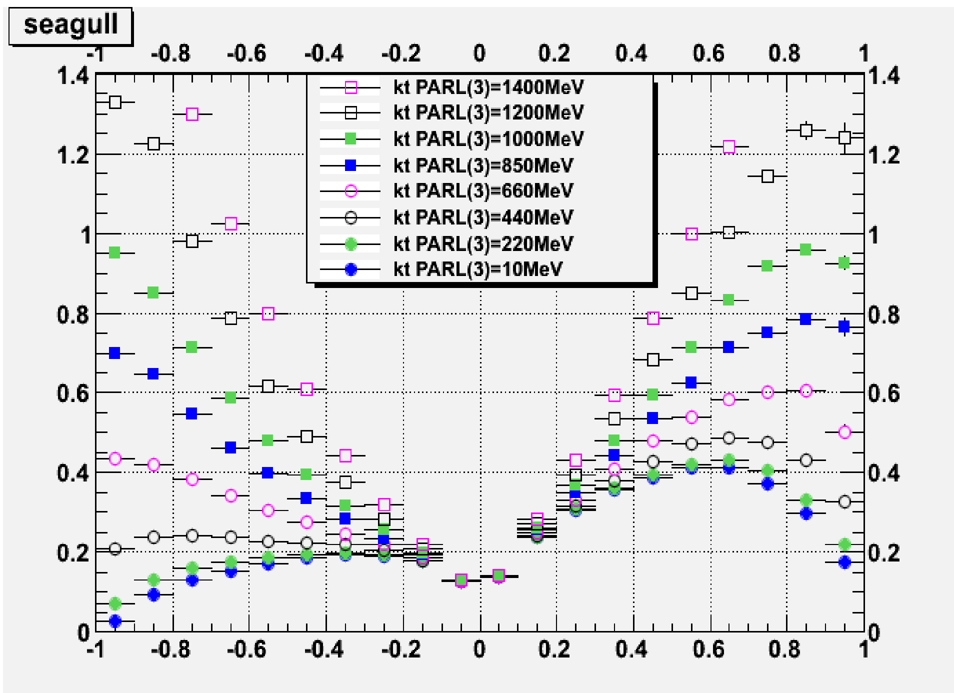
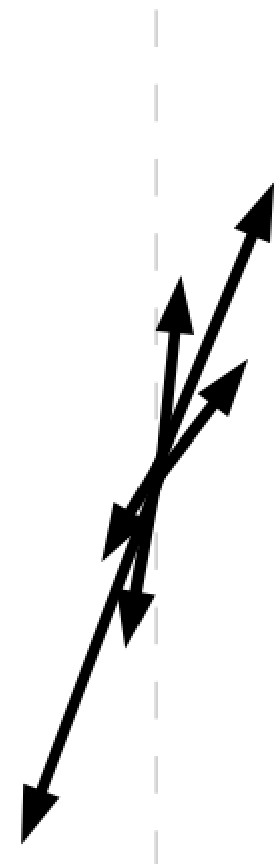
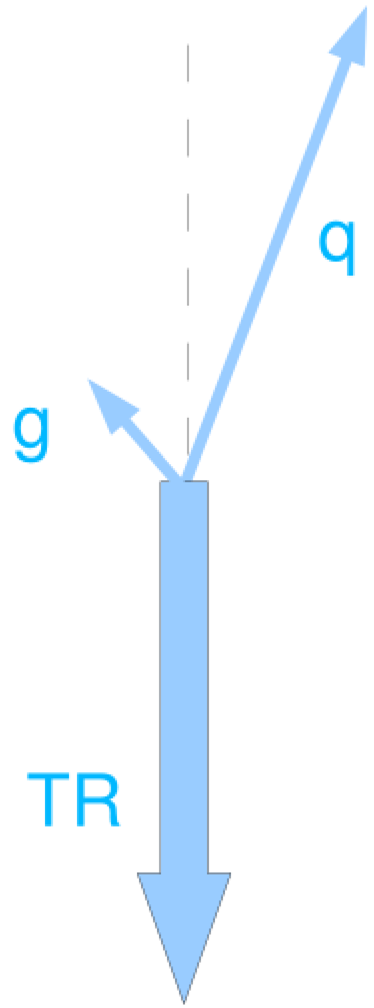
μp 490x0 or ep 5x50 GeV

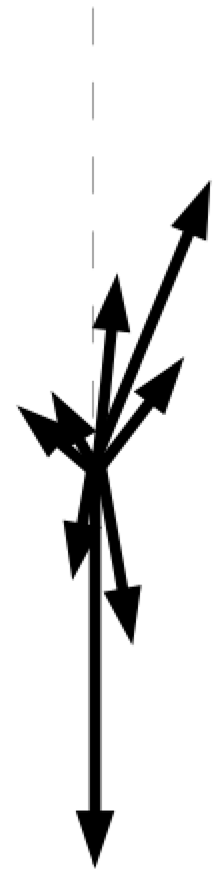


Contribution from primordial $k_T$ to $p_T$ grows with **$|x_F|$**

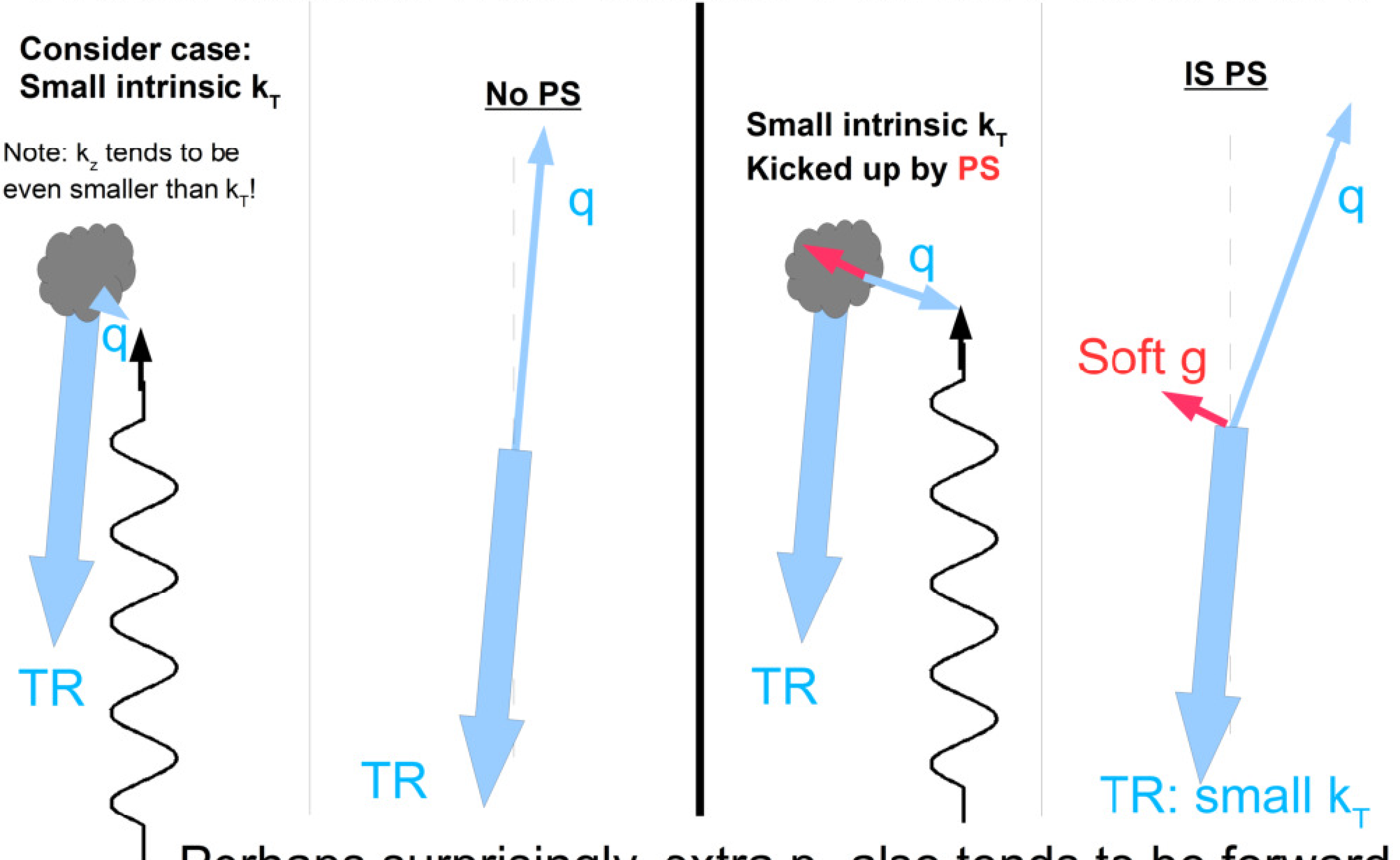
# QCD effects in hadronic cm



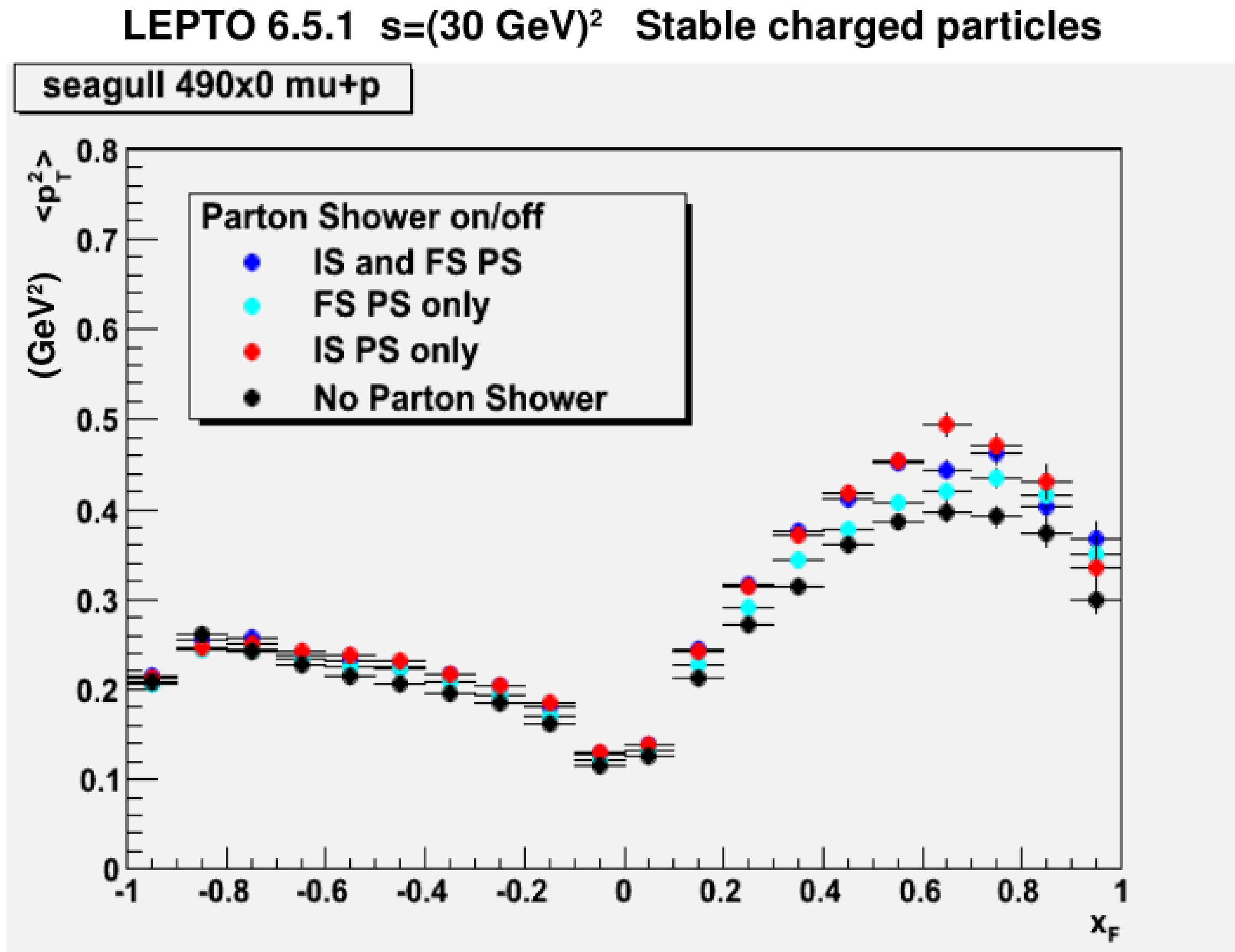
Hard QCD (and FS Parton Shower) increases $p_T$ at forward $x_F$

# What about Init. State Parton Shower?

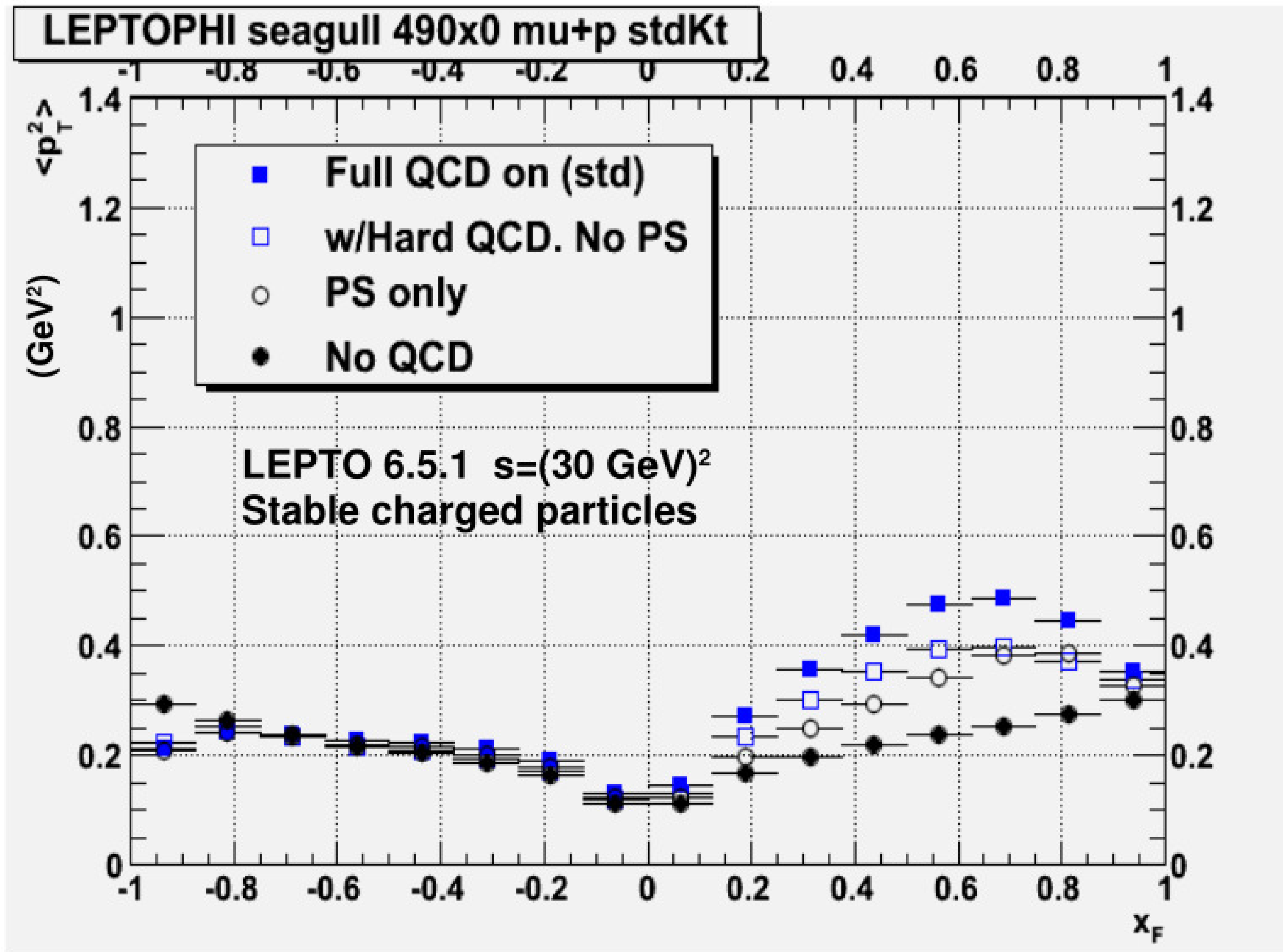



Perhaps surprisingly, extra $p_T$ also tends to be forward

# Parton Showers mostly contribute at forward $x_F$

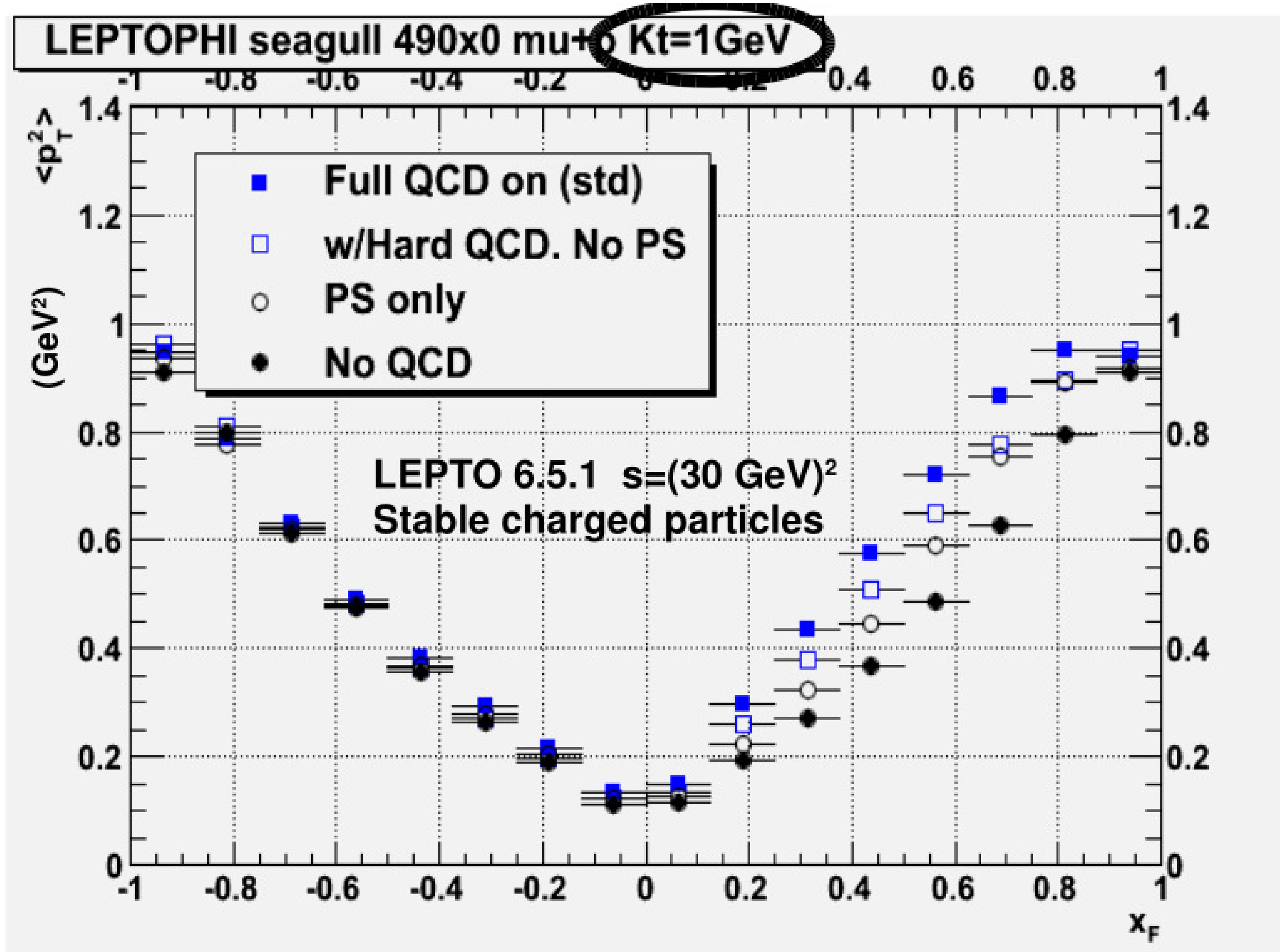


# QCD shows up at forward $|x_F|$



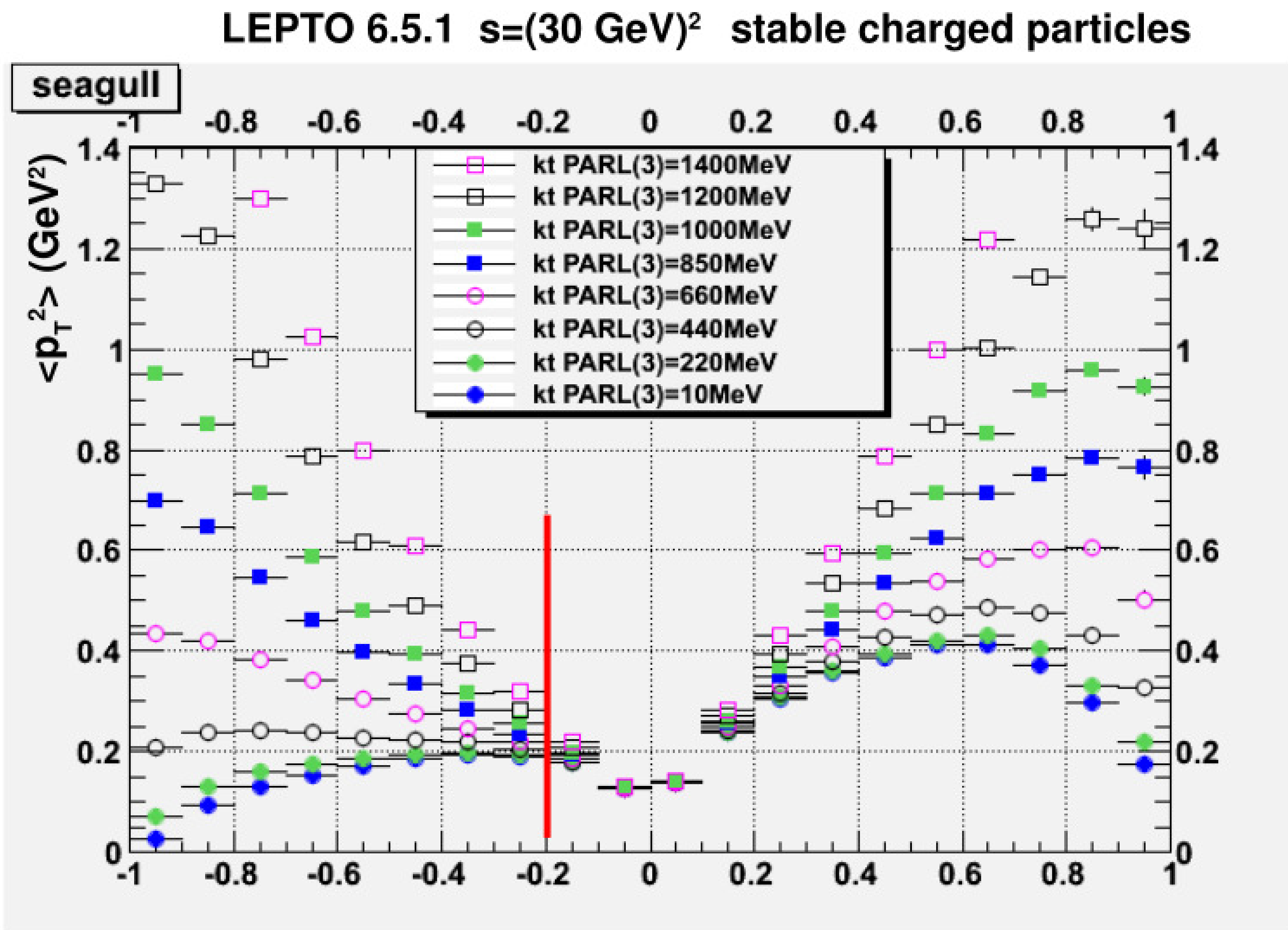

Basic physics: only the struck, accelerated, parton radiates

# QCD shows up at forward $|x_F|$




**Basic physics: only the struck, accelerated, parton radiates**

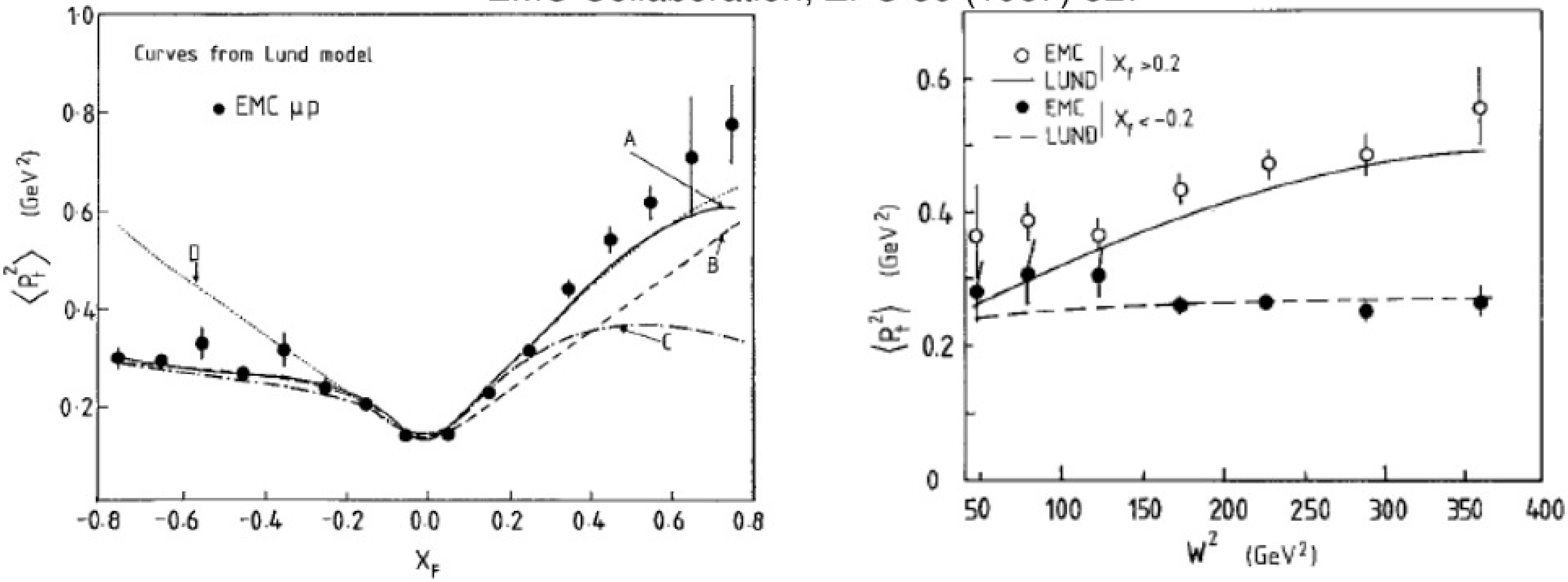
# Primordial $k_T$ cleanest at $x_F<-0.2$




Also shows up at $x_F>0.2$, especially for larger values of $k_T$

# EMC singles data

EMC Collaboration, ZPC 36 (1987) 527




A: Standard LEPTO w/ $k_T^{RMS}$ = 0.44 GeV (hard & soft QCD on)

B: Hard gluons off, soft still on

C: Soft gluons off, hard still on

D: Like case C, but w/ $k_T^{RMS}$ = 0.88 GeV

**0.88 GeV of kT looks VERY different than 0.44 GeV + soft QCD**

# Conclusion (singles)

- Intrinsic $k_T$ of struck parton:
  - Is reflected in the target remnant as well as struck parton (both forward and negative $x_F$)
  - Impacts hadron $p_T$ like $|x_F|\ k_T$
- Dynamical $p_T$ from soft or hard QCD shows up primarily forward ($\gamma^*$ direction in hadronic cm)
- Therefore intrinsic $k_T$ cleanest at $x_F$<-0.2
- Huge difference in seagull plot for rms $k_T$ of 0.44 GeV vs. 1.0 GeV

# Next step: hadron correlations

- Forward $p_T$ is a mix of $k_T$ and QCD
- Backward $p_T$ is a more direct indication of $k_T$
- And we have MORE information
  - Intrinsic $k_T$ shows up forward and backward equal and opposite

# Transverse momentum balance

- Trigger particle (two different plots)
  - Leading (largest $x_F$) particle with $x_F>0$
  - Leading (most negative $x_F$) particle w/ $x_F<0$
- Define the trigger particle $p_T$ direction as $p_x$
- Plot integral of other particles' $p_x$ vs. y*

**Definition from EMC, Zeits. für Phys. C 36 (1987) 527**

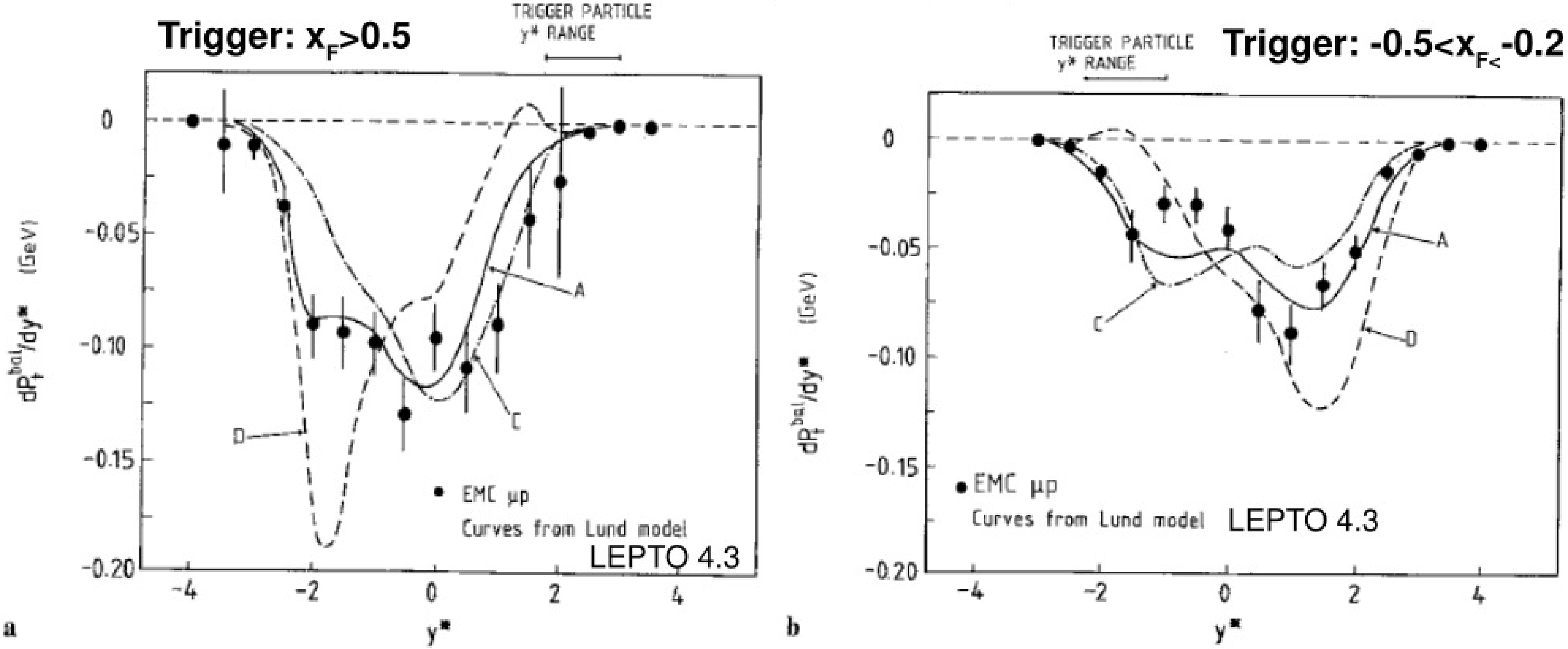
$$\frac{d p_T^{\mathrm{bal}}}{d y^*} = \frac{1}{N_{\mathrm{eV}}} \int p'_T \frac{d^2 N^{\mathrm{bal}}}{d p'_T \, d y^*} \, d p'_T$$

$$p'_{T_i} = p_T \cos \phi_i$$

where $\phi$ is the azimuthal angle in the cms system round the virtual photon direction with $\phi(\mathrm{trigger})=0$.

# EMC $p_T$ balance plots

EMC Collaboration, ZPC 36 (1987) 527




A: Standard LEPTO w/ $k_T^{RMS}$ = 0.44 GeV

C: Soft gluons off

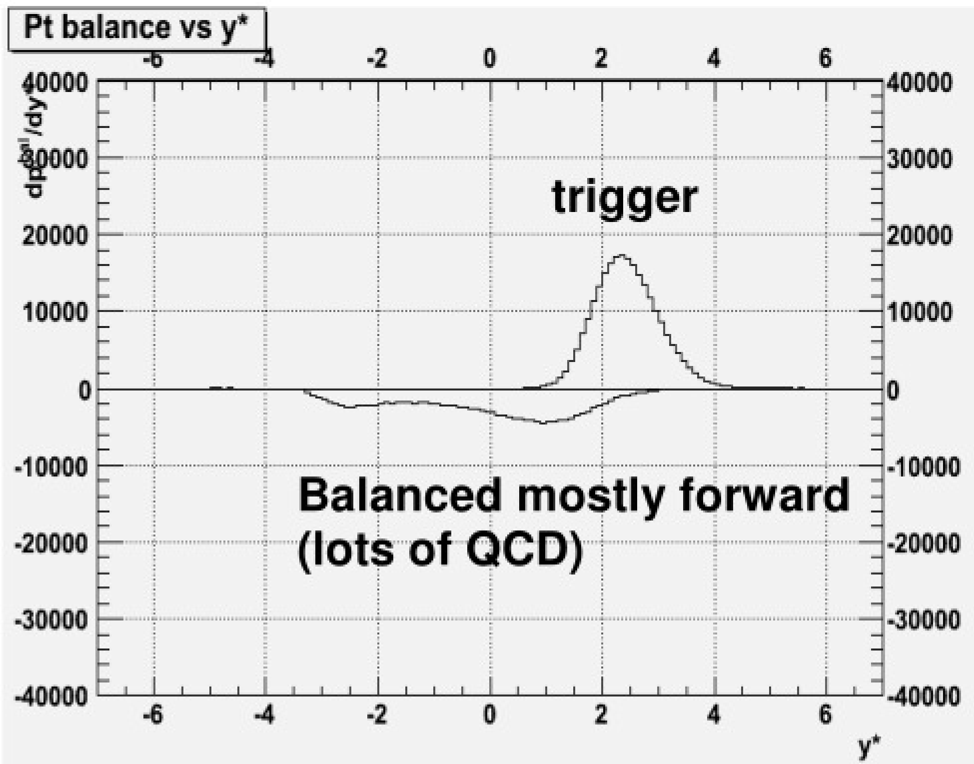
D: Soft gluons off, but w/ $k_T^{RMS}$ = 0.88 GeV

**0.88 GeV of kT looks VERY different than 0.44 GeV + soft QCD**
**This & the earlier EMC seagull plots were how LEPTO (even 6.5.1) was tuned**

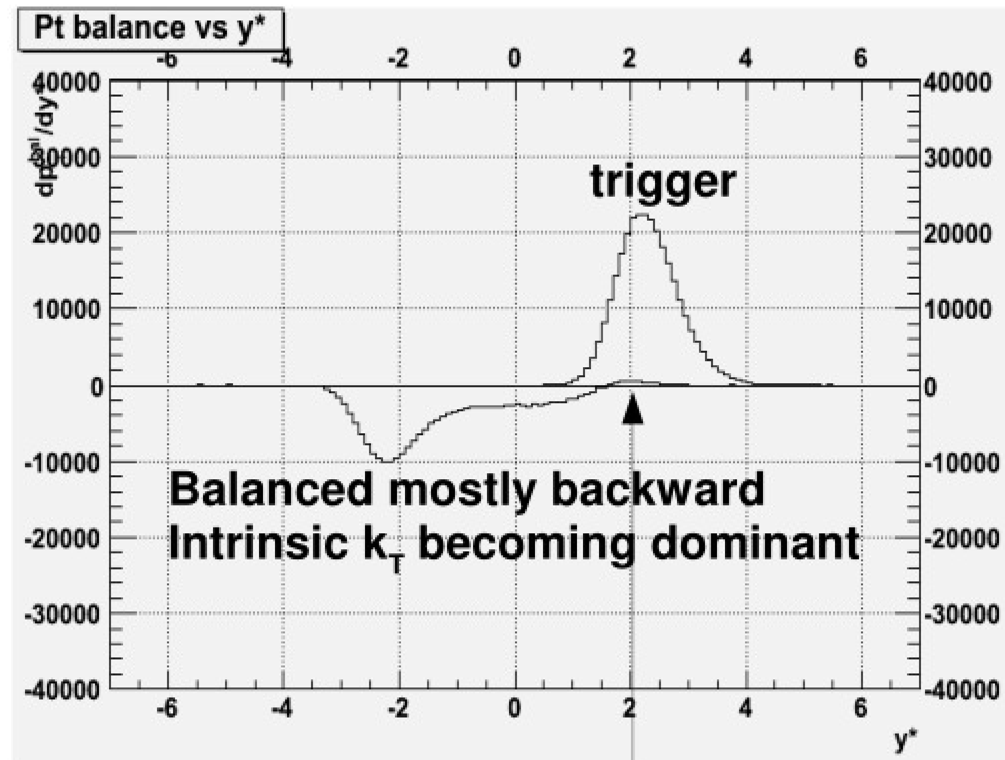
# Transverse momentum balance

LEPTO $s=(30\ GeV)^2$

**RMS $k_T$=0.44 GeV**




**RMS $k_T$=1.0 GeV**



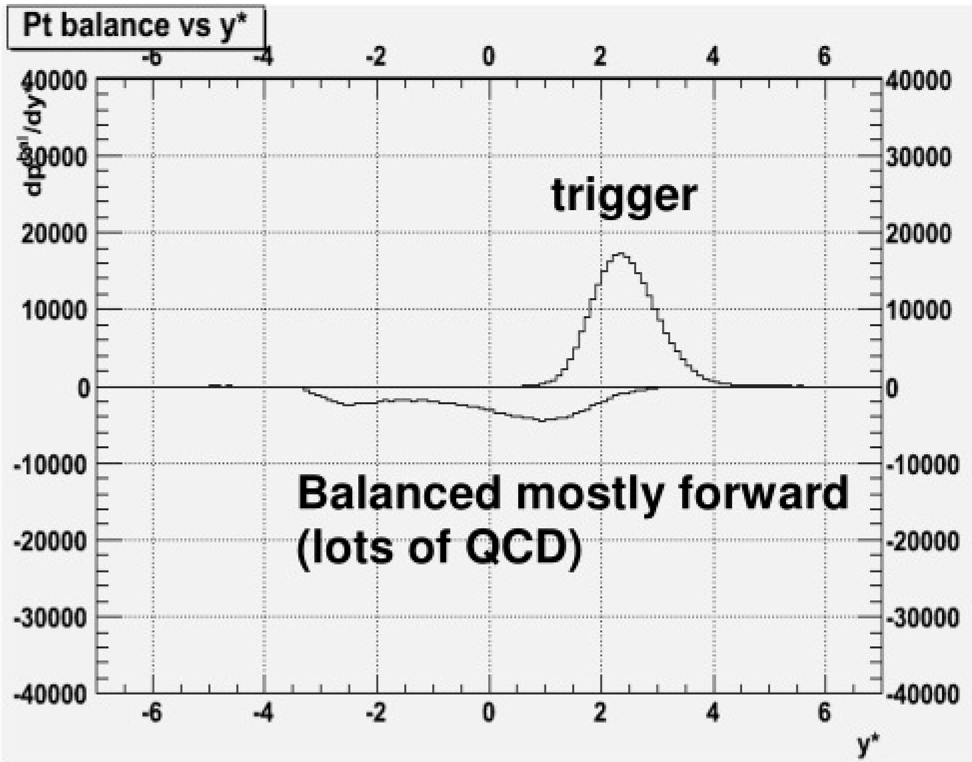

Note: These should be normalized by $1/N_{ev}$ and bin size $\Delta y^*$

**Very forward particles reflect positive $k_T$**

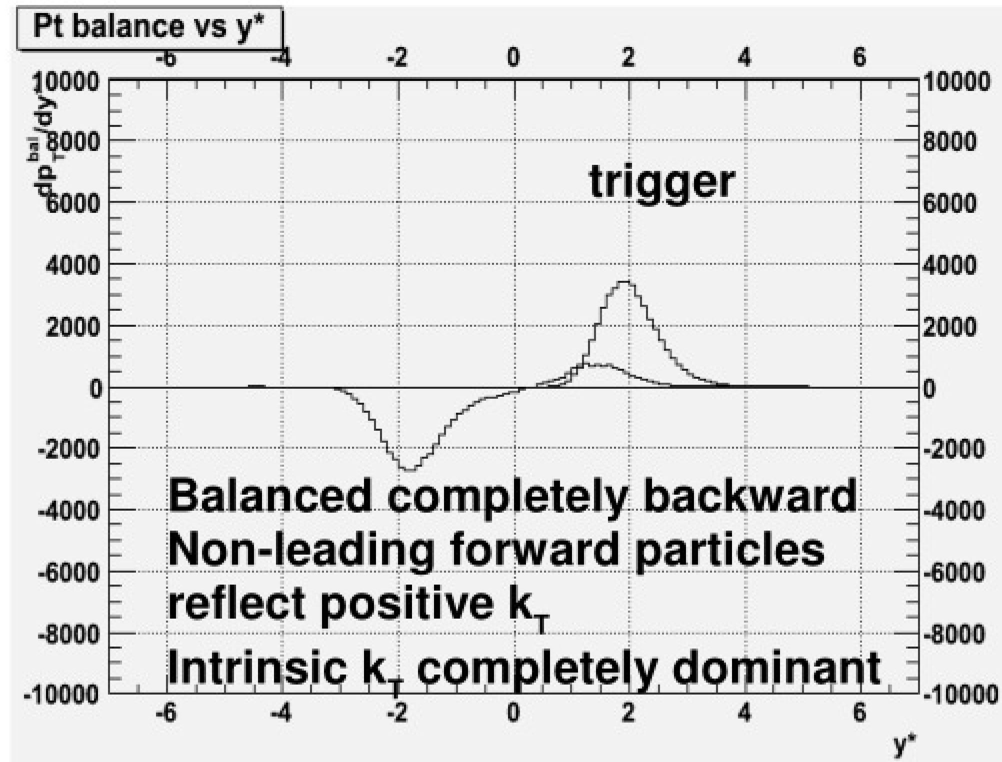
# Transverse momentum balance

LEPTO s=(30 GeV)$^2$

**RMS $k_T$=0.44 GeV**




**RMS $k_T$=2.0 GeV**

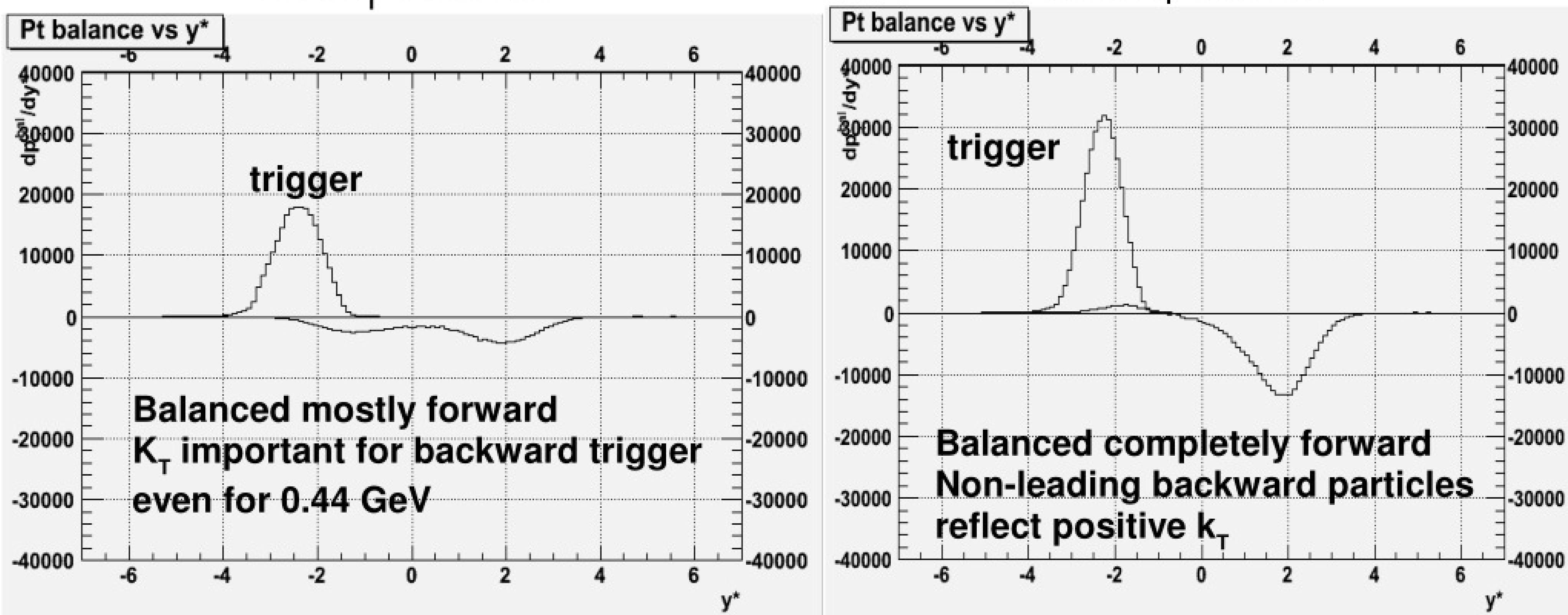



Note: These should be normalized by $1/N_{ev}$ and bin size $\Delta y$

# Transverse momentum balance

LEPTO $s=(30\ \mathrm{GeV})^2$

**RMS $k_T$=0.44 GeV** | **RMS $k_T$=1.0 GeV**




Note: These should be normalized by $1/N_{ev}$ and bin size $\Delta y^*$

**Intrinsic $k_T$ already dominant**

# Transverse momentum balance

LEPTO s=(30 GeV)$^2$

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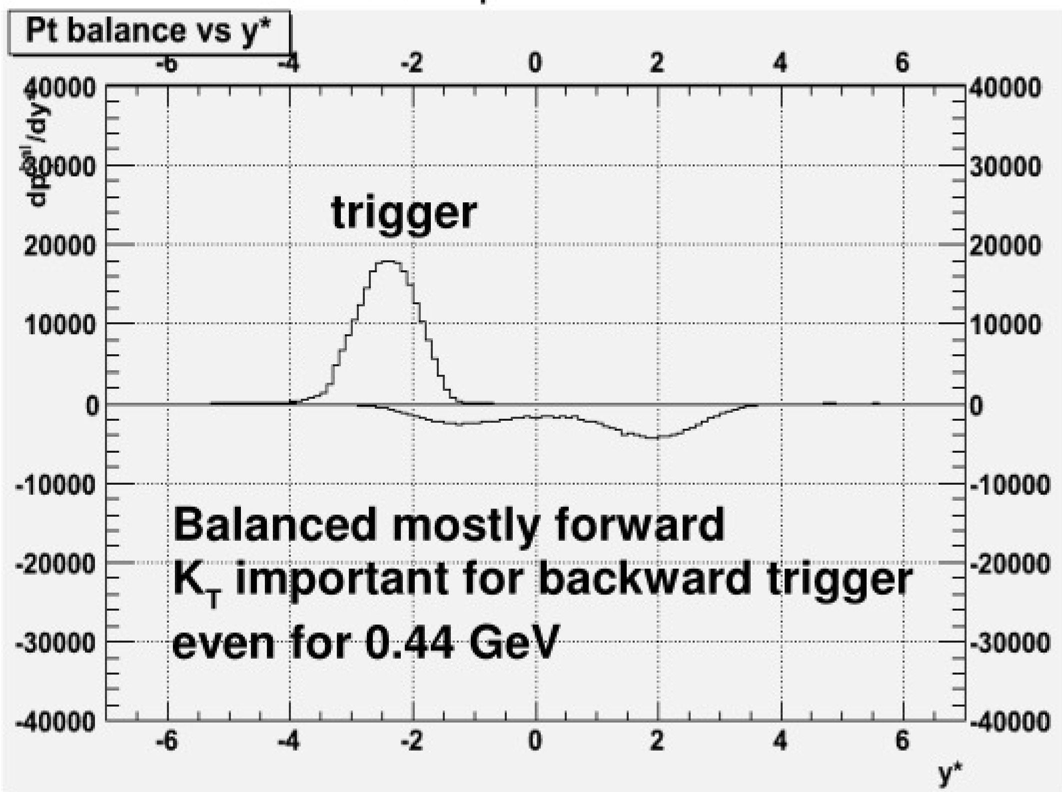


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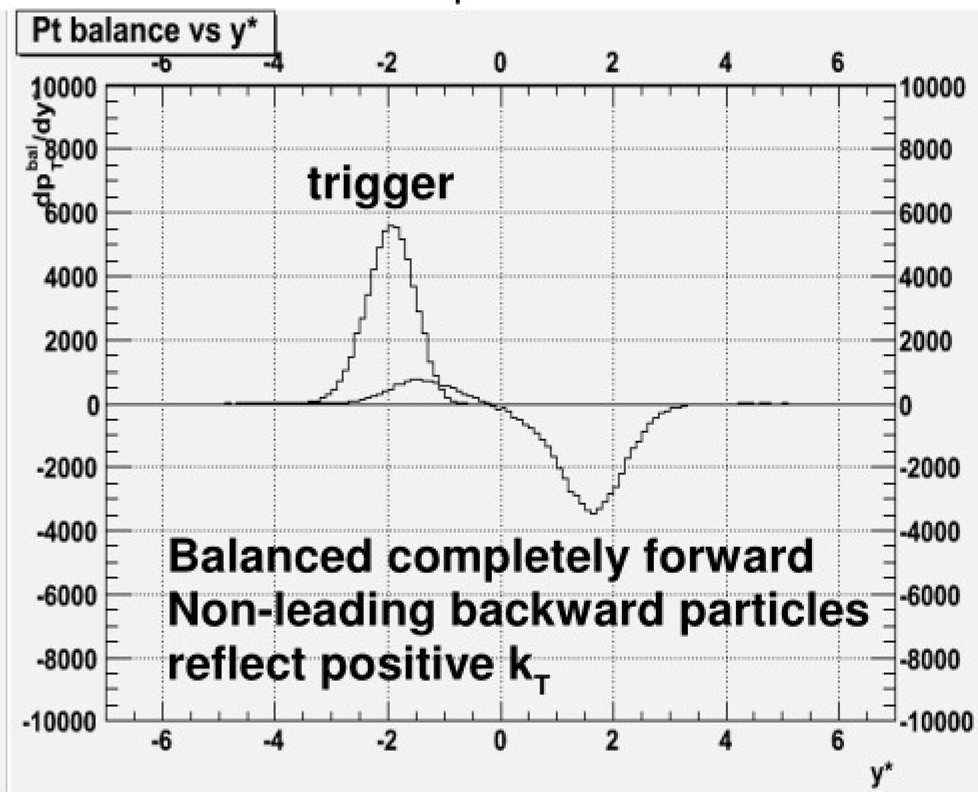


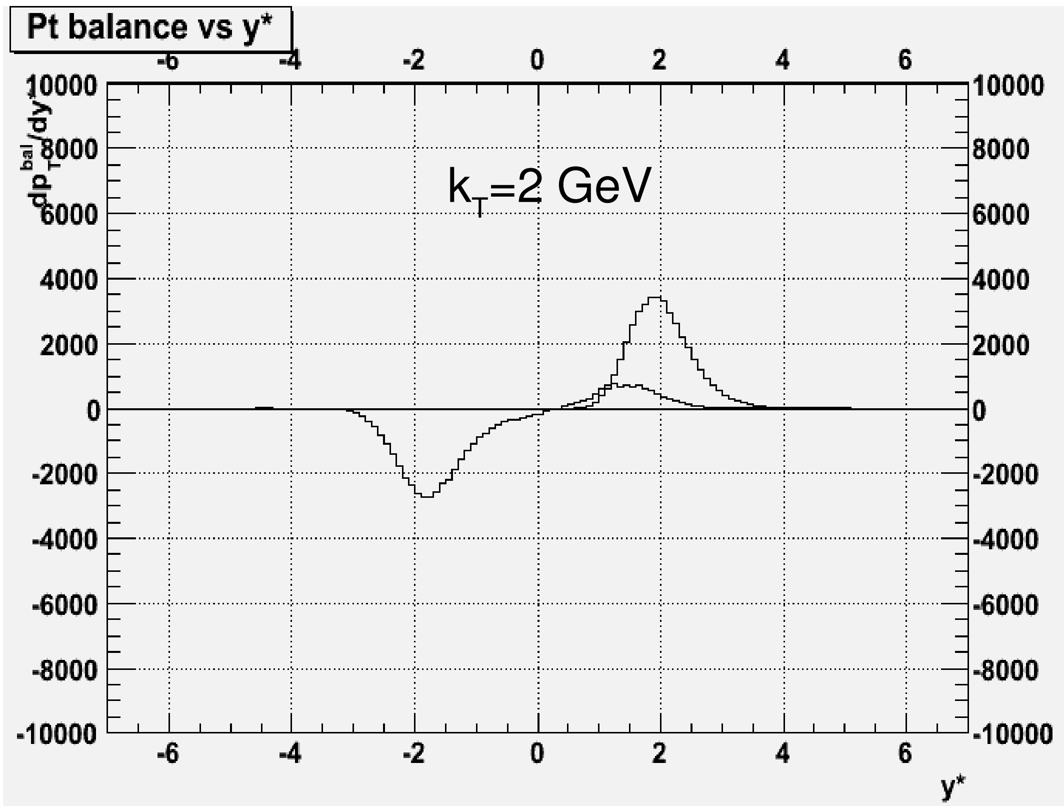

Note: These should be normalized by $1/N_{ev}$ and bin size $\Delta y^*$

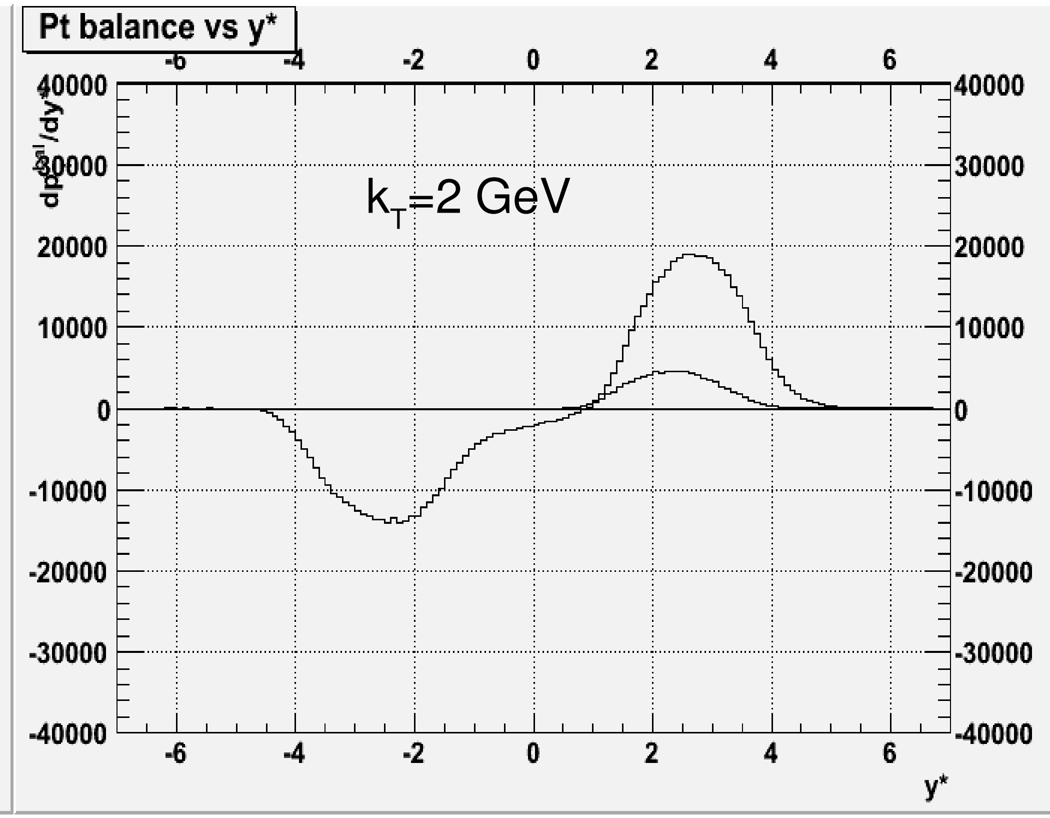
**Intrinsic $k_T$ dominant**

# Effect of different beam energies

LEPTO 6.5.1 s=(30 GeV)$^2$
μp 490x0 or ep 5x50 GeV

LEPTO 6.5.1 s=(140 GeV)$^2$
ep 20x250 GeV

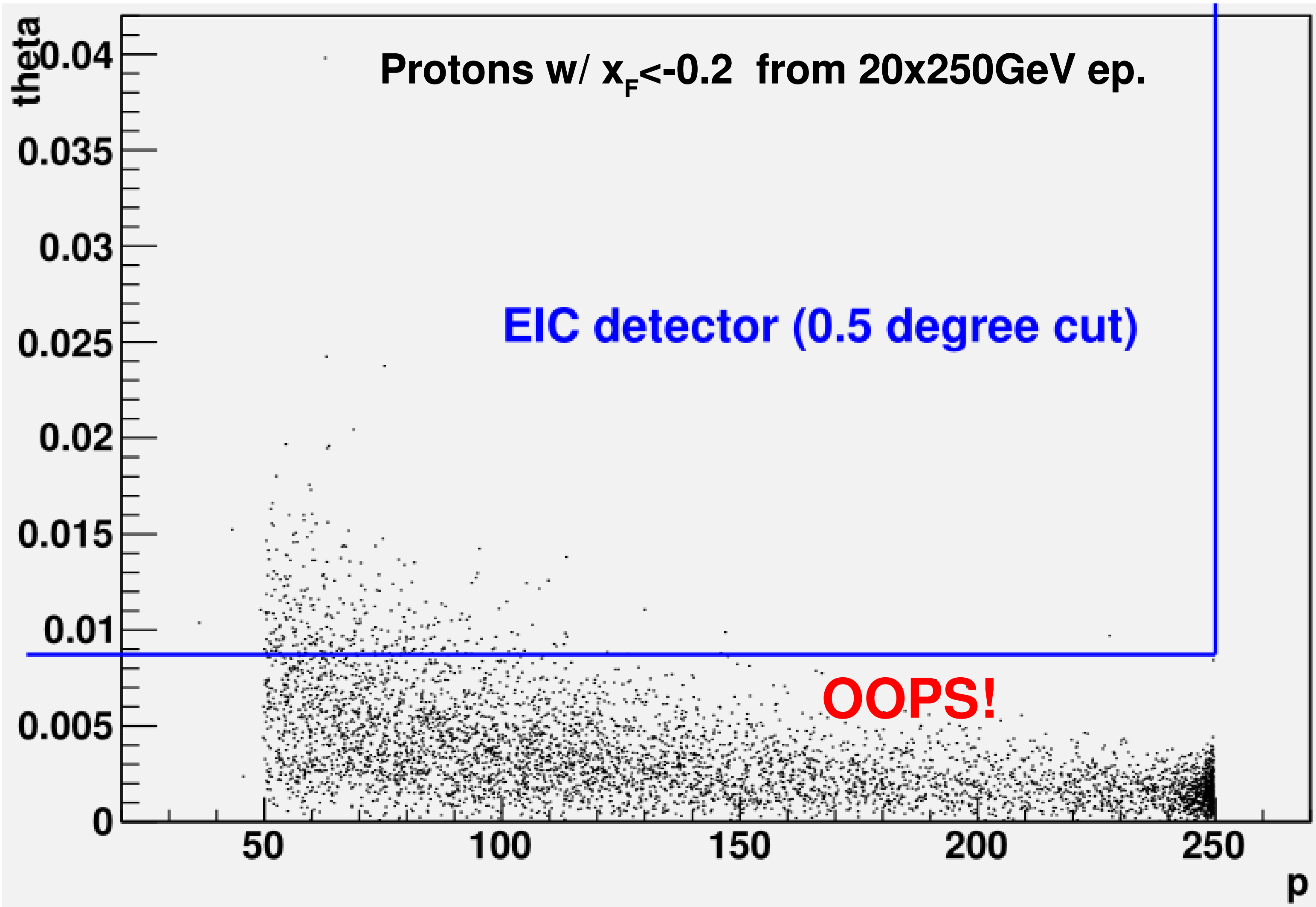



Note: Arbitrary units on $dp_T^{bal}/dy^*$ scale
(not divided by $N_{ev}$ & $\Delta y^*$)

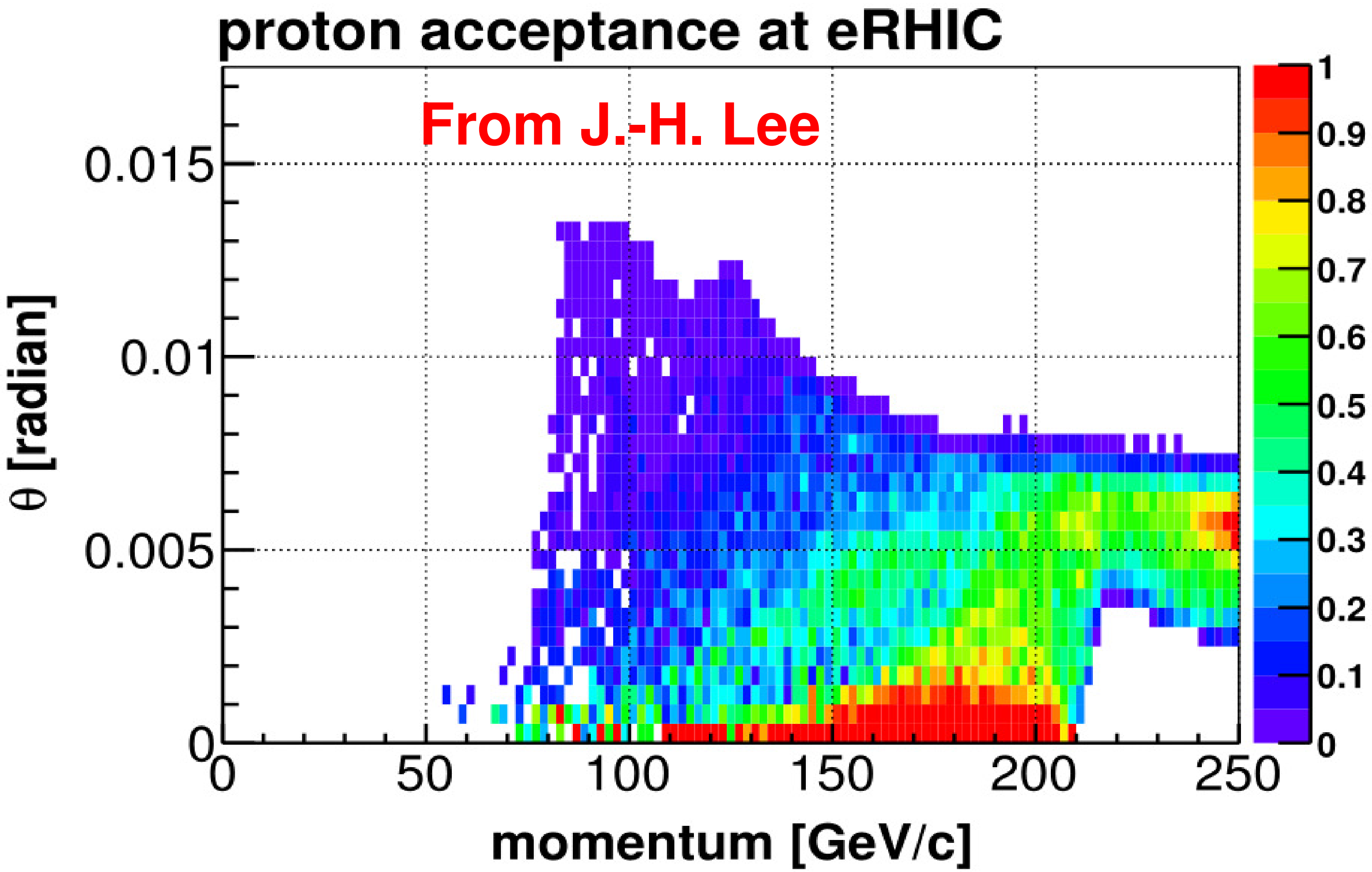
# Where are these $x_F$<-0.2 particles?

(radians)




$\Theta = 0$ means the proton beam direction

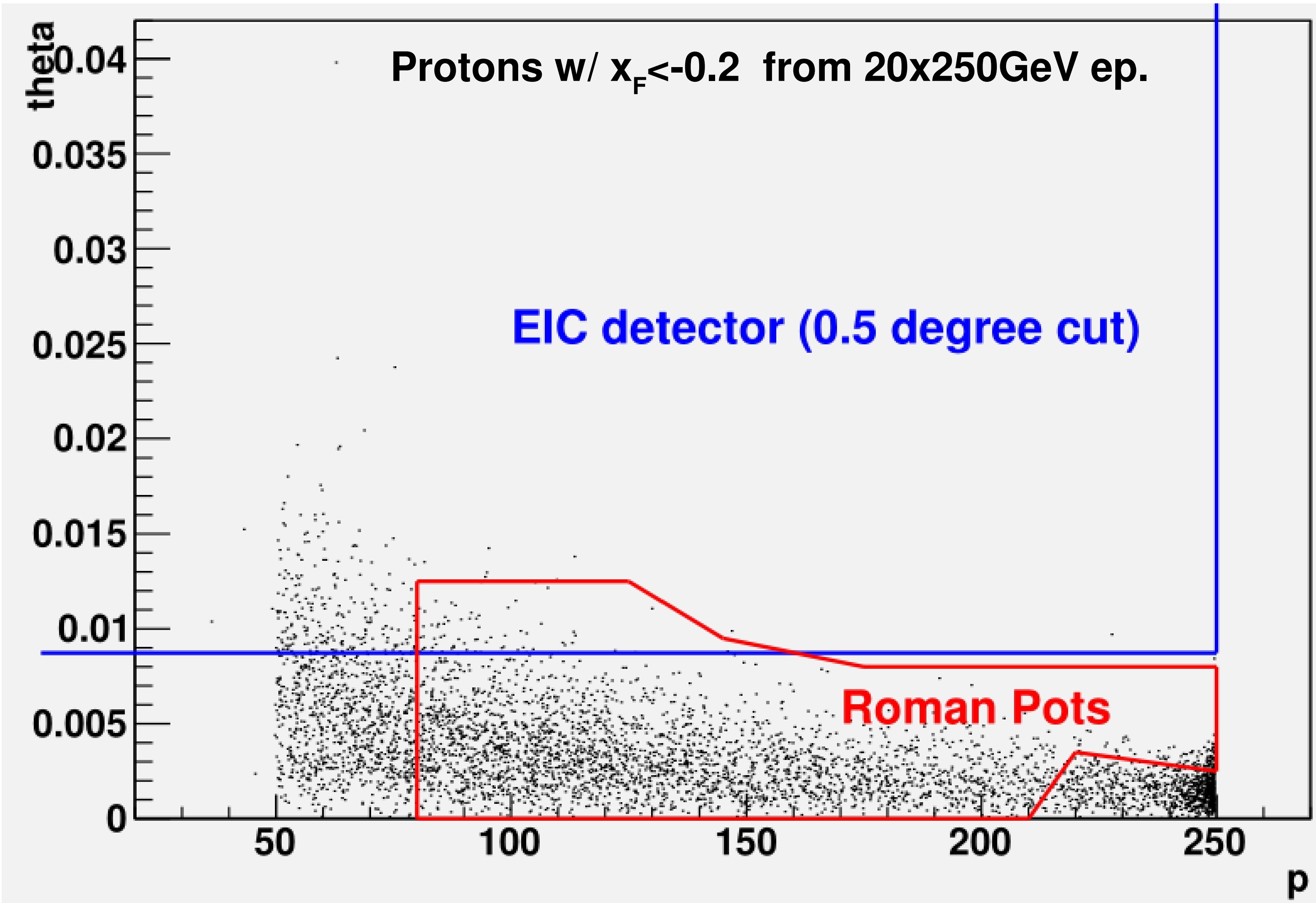
# Roman Pot Acceptance!



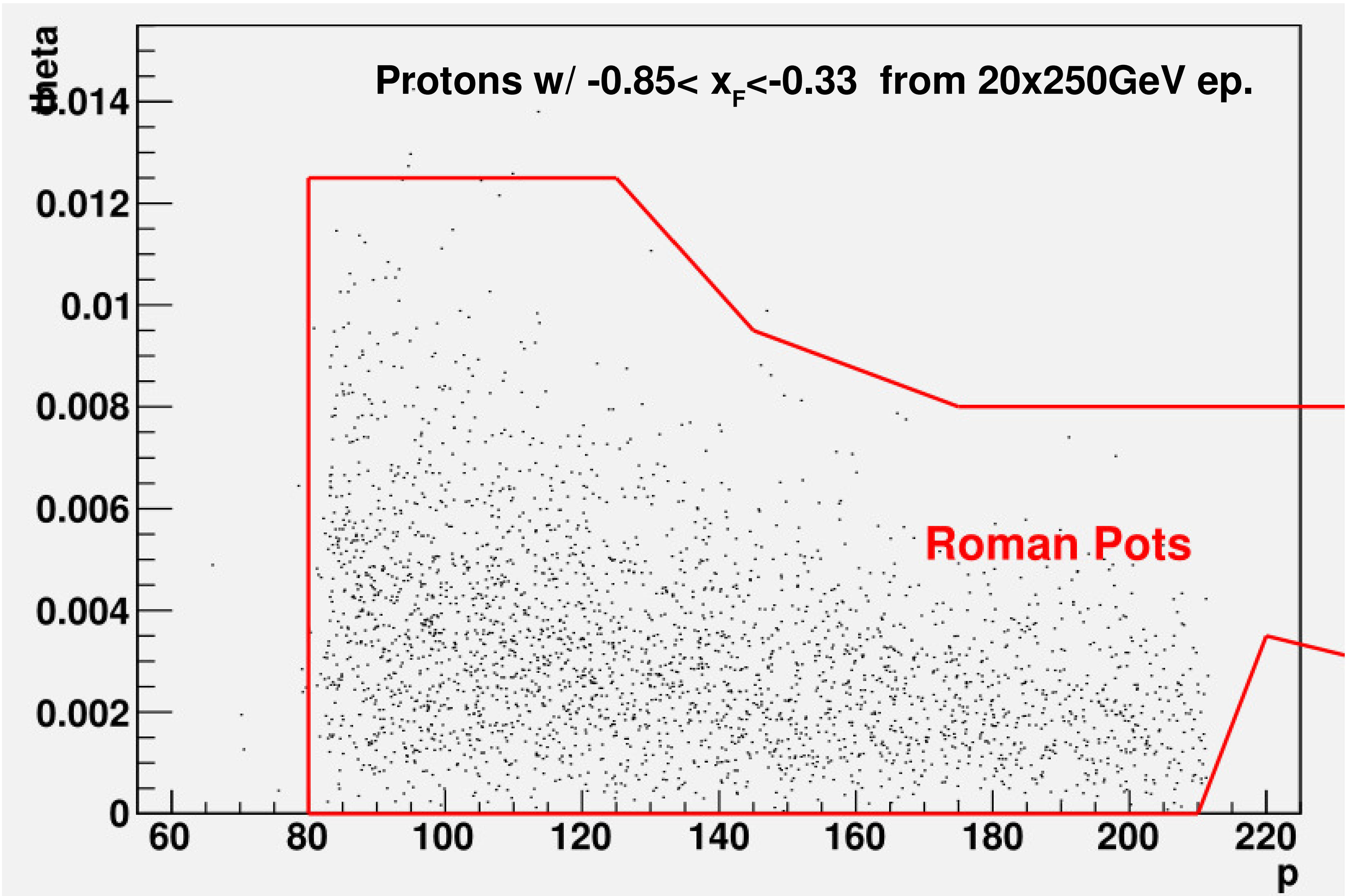

Note: Uses June 2011 eRHIC optics – probably will be less generous in the end.

# Roman Pots save the day!

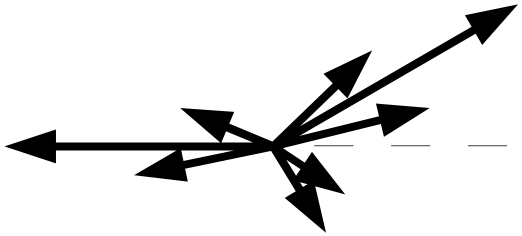
(radians)

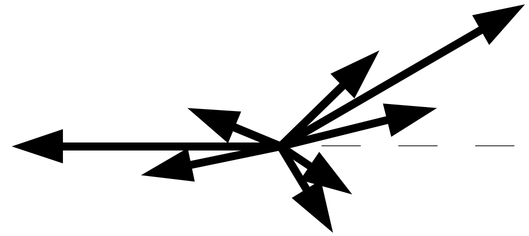


# We're in business.



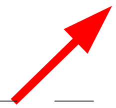
# Complementary correlations: QCD

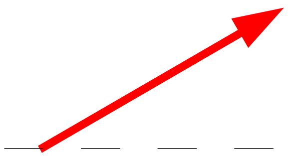




Di-hadron trigger particle (0.1<z<0.3)

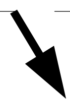
$p_T$ comp. trigger particle

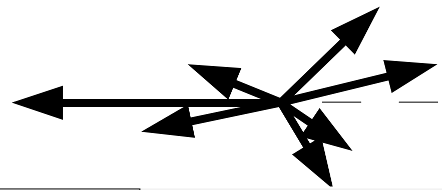


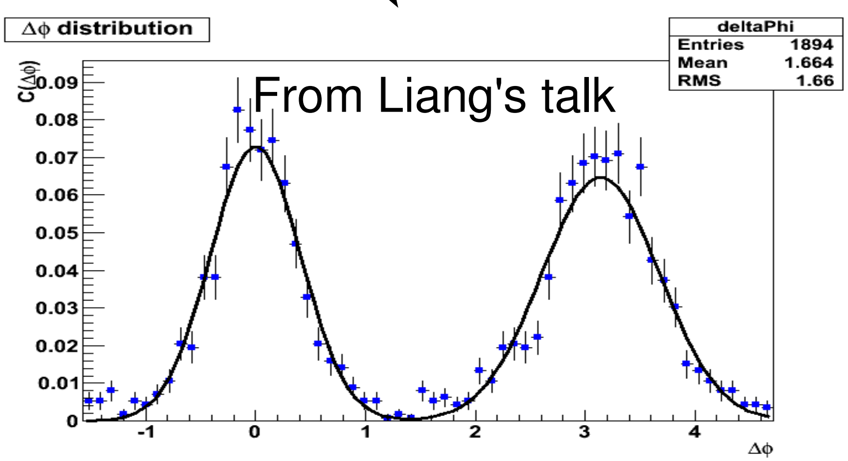


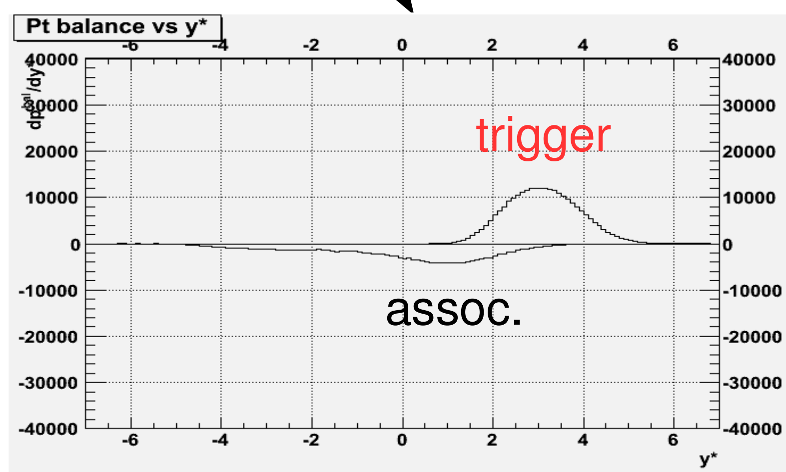
Di-hadron assoc. particle

$p_T$ comp. assoc. particles

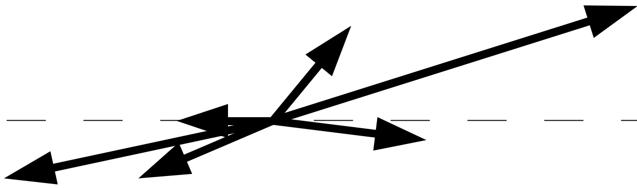


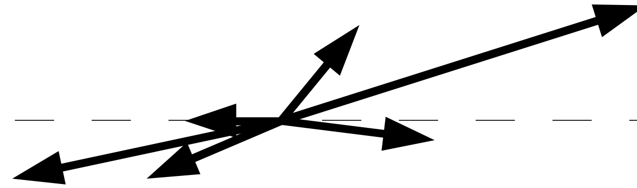




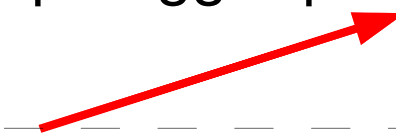
# Complementary correlations – $k_T$





Di-hadron trigger particle (0.1<z<0.3)

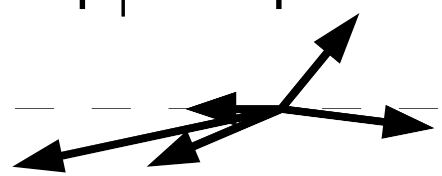
$p_T$ comp. trigger particle

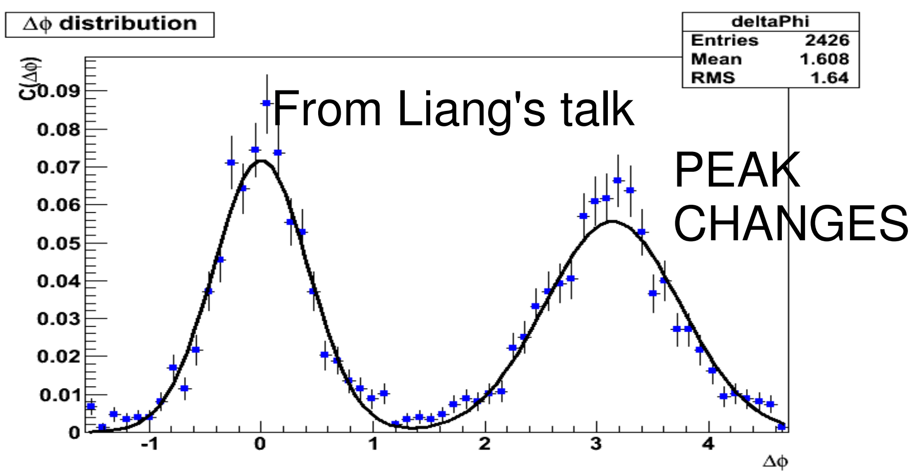


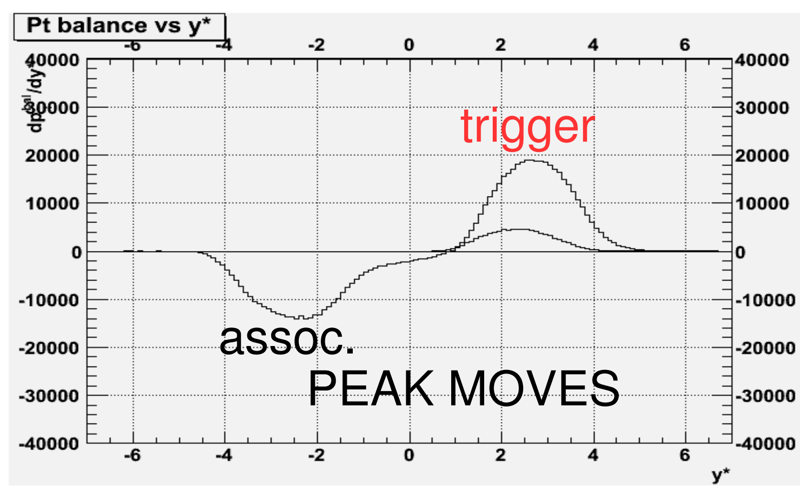
Di-hadron assoc. particle

**(NONE)**

$p_T$ comp. assoc. particles





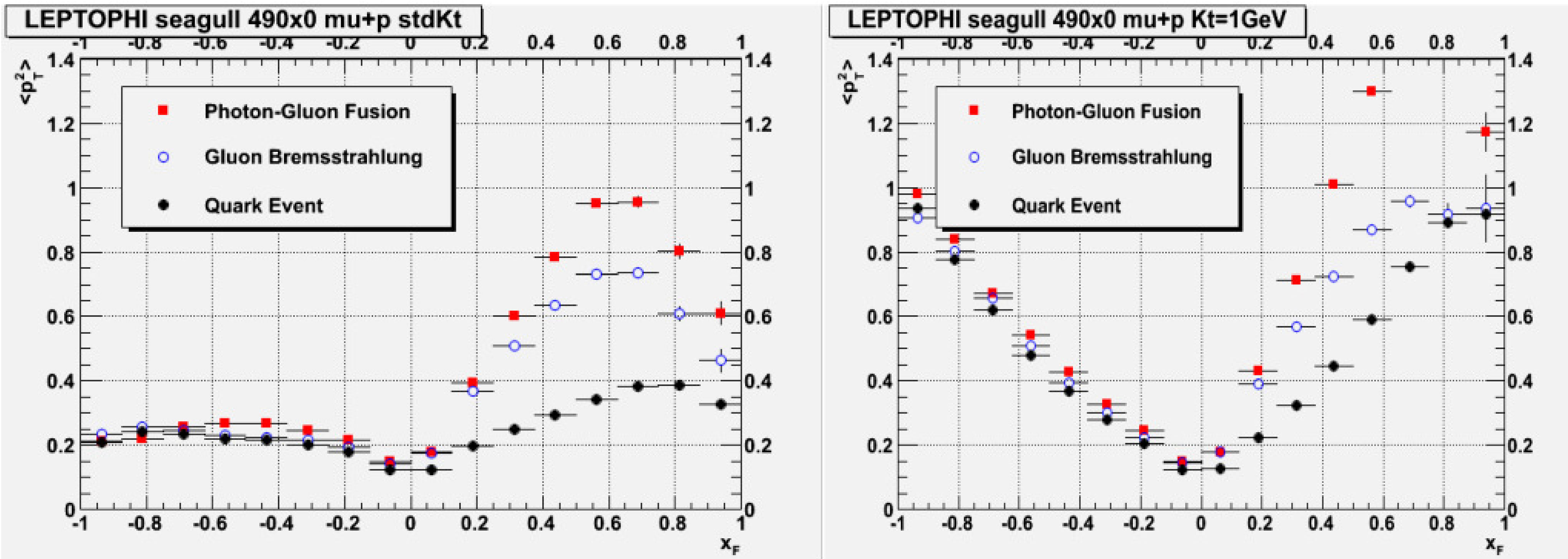



# Additional idea to pursue...

- Dijet correlation but trigger particle having $z>0.3$ rather than $0.1<z<0.3$.
- Associated particle still with $0.1<z<0.3$.

# Gluon $k_T$

Gluon and sea quark kT must be highly correlated, but lets look at what might happen if we tag photon-gluon fusion events:




**Backward hemisphere very sensitive to kT and doesn't care about subprocess. If gluon and quark kT are different, this is a clear way to see it!**

Note: My LEPTO-PHI version has the ability to make gluon kT different than quark kT

# What about eA? (Saturation!)

- Seagull plot is more model-dependent:
  1) Intranuclear cascade at negative $x_F$
  2) If $k_T$ increased due to saturation effects, multiple nucleons may share the recoil from the struck parton $k_T$.
- $p_T$ compensation plot probably still very useful.
  1) kT recoil will still be at $x_F$<-0.2, it may just be shared differently.

  NOTE: We actually have good acceptance for $x_F$=-1 protons from eA!

# What about Drell-Yan in pp

- There is not a completely obvious generalization of this approach to DY.
- It is probably possible to construct a correlation between a leading proton $p_T$ and the lepton pair $\Sigma p_T$.
- Even better would be those events where we could catch BOTH beam remnants and correlate their $\Sigma p_T$ with the lepton pair $\Sigma p_T$.

# Conclusion

- Effect of large intrinsic $k_T$ (1-2 GeV) looks very different from hard or soft QCD effects in DIS:
  - Seagull plots and general $p_T$ at high $|x_F|$
    - Especially $x_F < -0.2$
  - Forward-backward $p_T$-balance correlations
- For gluon $k_T$ the backward hemisphere is even more critical to use since the forward hemisphere is contaminated with QCD.